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Assessment of Current Onsite Inspection Techniques for Light-Water Reactor Fuel Systems

Discussion of Inspection Techniques

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Prepared by W. J. Bailey, C. J. Morris, F. R. Reich, K. L. Swinth

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Prepared by
W. J. Bailey, C. J. Morris, F. R. Reich, K. L. Swinth

Pacific Northwest Laboratory
Richland, WA 99352

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PREFACE

To meet the legal requirements of Pacific Northwest Laboratory (PNL) for release of this document, it was necessary to code the companies (i.e., fuel vendors, utilities, etc.) discussed in this report. Ranking of companies is not intended or implied with this coding system. PNL sent information regarding the code (and some associated references) to the Nuclear Regulatory Commission under separate cover.

Volume 1 was published in July 1980 and involved References 1-23. Repeated below are a few comments from Volume 1 regarding the use of the terms accuracy, precision, and resolution:

- The Metals Handbook (Ref. 22) uses these definitions:
  Accuracy - "The closeness of approach of a measurement to the true value of the quantity measured. Since the true value cannot actually be measured, the most probable value from the available data, critically considered for sources of error, is used as the 'truth'."
  Precision - "The closeness of approach of each of a number of similar measurements to the arithmetic mean, the sources of error not necessarily being considered critically. Accuracy demands precision, but precision does not require accuracy."
  Resolution - "The ability of an optical or radiation system to separate closely related form or entities; also, the degree to which they can be discriminated."
- NUREG-0650 (Ref. 23) states that accuracy is the agreement between the true value and the result obtained by measurement, and precision is the agreement among repeated measurements of the same quantity.

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5. VISUAL INSPECTION

5.1 Introductory Comments

In evaluating visual inspection techniques, one must keep in mind that visual inspection is a subjective task using the visual faculties of a trained technician and some imaging aid, such as a binocular, periscope, or underwater closed-circuit television (CCTV) system (Figure 3.1). With PWR fuel and dechanneled BWR fuel, the fuel rod surface that is visually accessible in any fuel bundle is very small, and only a minor portion of the peripheral fuel rods are visible without an instrument that penetrates the bundle. Quantitative judgments as to whether a particular visual response is abnormal and warrants further investigation depend on the operator's basic abilities and his mental and physical condition.

An extensive literature search on poolside visual inspection was performed and very little published literature was found. Most of the literature available presented only summarized data, with very little detailed description of equipment and no references to documents that would contain detailed data. The large and recent interest shown by the Electric Power Research Institute (EPRI) in poolside inspection (by visual and other techniques) has spurred many ongoing fuel inspection programs that are well documented. Many of these inspection programs are not completed, so the literature from them was not publicly available during the writing of this report. The bulk of the data on poolside inspection was obtained from direct discussions with fuel vendors and with utilities at operating power reactor sites.

5.2 Visual Inspection Methods

In the visual inspection of reactor hardware and fuel system components, the basic inspection techniques are:

- direct visual observation through the pool water by a poolside observer
- underwater CCTV cameras with the television (TV) monitor positioned on the deck by the pool

- optical periscope.

The bulk of reactor hardware and fuel cursory inspections are made by a technician using a simple optical binocular from a poolside observation point. This inspection method is simple and can be quickly initiated to respond to any need. No special handling hardware is required as the technician can locate himself at the best observation position, and the existing fuel handling equipment in the reactor and pool areas can provide fuel bundle rotation. To inspect the bottom of a fuel bundle, a simple flat mirror is used.

A CCTV system consists of an underwater radiation-resistant TV camera and deck-side TV monitor. To date, all of the radiation-resistant camera systems commercially available are black and white units. CCTV cameras may be mounted on both fixed or scanning frameworks. In either case, a scan over the fuel bundle length must be made to view one total side of the bundle. A waterproof signal and power connection is necessary between the camera and monitor. To assist in data acquisition, a video tape unit is used in all fuel bundle and rod inspections. A continuous visual record of the fuel rod scan can be made. The TV monitor and video tape units are generally located near the camera unit, so visual observations can be easily used to verify the inspection handling operations. Since some spent fuel storage pools have only limited deck space on their perimeters, space for equipment setup may be severely limited or prohibited. The cask loading area is generally used for this inspection because it has some deck space and is usually free from interference with the crane used for moving fuel bundles in the pool. All elements of a nuclear CCTV are designed to be radiation resistant and can tolerate an exposure level in the Roentgen range.

An optical periscope is similar to one optical channel of a binocular but with a large separation between the objective lens and the operator's eyepiece. This separation between the objective lens and eyepiece is an optical relay and serves to transport the image from the objective lens to a position where it can be viewed with the eyepiece. The optical relay allows the objective lens to be close to an object to maintain high resolution and light collection and, in the case of a spent fuel bundle, still keep the observer a safe distance

from the viewed object. The optical relays are made in fixed length increments, so the objective lens-to-eyepiece separation cannot be changed for a poolside installed periscope. To view the total length of a fuel bundle, either the periscope or fuel bundle must be moved. To maintain image stability, the periscope must be solidly mounted to either the edge of the pool or to a stable platform in the pool. Fuel bundles are then transported to the periscope and manipulated in front of the objective lens for visual inspection.

5.3 Surface Visibility in Poolside Inspection

There is a severe limitation on the surface visibility of fuel bundles for any visual inspection technique. With all fuel bundles, the upper and lower end fixtures (i.e., tie plates, nozzles, and end fittings) are visible, although a mirror or tiltable CCTV (or periscope head) must be used to look under the fuel bundle to see the bottom of the lower end fixture (unless the fuel bundle is placed in a horizontal position).

With a PWR fuel bundle or a dechanneled BWR fuel bundle, there is limited visibility of the fuel rod surfaces. With an external viewing aid, such as a periscope, one can only see about three fuel rod rows deep. One fuel vendor stated that about 50% of the surface of the peripheral fuel rods is visible, approximately 10% of the surface of second-row fuel rods is visible and only a small part of the surface of third-row fuel rods is visible. With a typical PWR fuel bundle, another fuel vendor stated that approximately 15% of the fuel rod surfaces can be visually examined (i.e., 30% of all the fuel rods in the bundle are visually accessible and 50% of their surfaces are visible).

With single fuel rods, the total fuel rod surface is visually accessible, but the rod must be rotated to view this total surface. Because of optical specularity, a fuel rod is difficult to illuminate uniformly even when only one side of the rod is viewed. Unless there is a diffusing crud layer, the illuminating sources generally produce bright specular bands on the rod surface, making viewing and recording of surface details optically difficult because of the large intensity difference between specular and nonspecular imaged areas. A 360^{o} circumferential view of the fuel rod is obtained by physically

manipulating a fuel rod in an inspection station. No references to optical systems with a full 360° fuel rod surface view in one optical system were found.

A decrease in the clarity of pool water can also decrease poolside inspection visibility. Movement of fuel can cause a reduction in water clarity, especially when a large number of fuel bundles have been moved into or within the pool in a short time. There are no specific water clarity standards for poolside inspection, although applicable turbidity instrumentation is available commercially. As a rule, periscope systems tend to be less sensitive to water clarity problems than TV systems because the optical path lengths require somewhat higher incidence angles for illumination and also have a smaller particulate volume, which would reduce the magnitude of optical backscatter from suspended crud. No references to the use of special filtered water curtains to keep particulates out of the optical path length and flowing away from the viewing area were found in this study. Although the illumination parameters can also affect the poolside image quality, no general guidelines for illumination levels (spectral content or geometry) were made available for this study. Because a visual inspection task is highly subjective, apparently the optical parameters affecting the image visibility (such as illumination and image clarity) are also controlled by similar subjective judgment rather than by nonsubjective mensural techniques.

5.4 Hazards to Fuel From Inspection

The hazards to fuel rods and fuel bundles from poolside visual inspection are associated with fuel handling and not the visual inspection process. Potential hazards include dropping of fuel rods or bundles and collisions with inspection fixtures. Usually, care is taken to properly support the fuel rod or bundle so no unnatural stresses are imposed. One of the more subtle hazards is the insertion of fuel rods into wrong positions in a fuel bundle that is being reassembled. Precautions, such as a dual visual verification and a "one-for-one" movement schedule for fuel rods, are used to help maintain the fuel bundle makeup. Mechanical design precautions are enforced for all fuel rod/bundle contacting guides or hardware, and load cells are employed to prevent large

abnormal forces from being applied to fuel bundle components. Fuel handling fixtures are usually designed with full rod and bundle support during an inspection, such as the use of special fuel rod and fuel bundle elevators. During handling of fuel for poolside inspection, a few fuel rods and bundles have been dropped or scraped, a fuel rod has been bent, and some spacer grids have been damaged or scraped.

5.5 Poolside Visual Inspection Techniques

In reviewing the data, it is evident that there are basic generic differences in poolside inspection techniques and in the empahsis placed on visual inspection. During many reactor refueling outages, some form of visual observation and an optical system, such as a simple optical binocular, is used. For more detailed visual inspection, the type of optical equipment varies with the utility's or fuel vendor's approach to the total poolside inspection task. There is no consensus on which viewing aid is best for visual inspection or on the importance of image color in the poolside inspection process.

5.5.1 Poolside Inspection Data

Because each poolside inspection campaign is unique, the visual inspection aids are usually chosen to fit the inspection needs and schedules. In general, very little on-the-spot analysis is done; records of anomalies (photographs), along with verbal comments, are prepared for later analysis. Visual inspection is not considered a primary tool for the identification of failed fuel. Fuel is inspected for basic anomalies and for specific fuel characteristics (some are prescribed by the overall poolside inspection guide for the outage) or photographed and comments from the lead inspector recorded for a later detailed analysis of the poolside inspection data.

The use of poolside inspection data varies with each vendor. For example, one fuel vendor's needs are for bench mark fuel data, fuel design verification, and fuel code development. Another fuel vendor, on the other hand, uses much of the poolside inspection information to update fuel codes. Therefore, their inspection technicians may have more freedom to explore anomalies. Inspection standards are subjective and are part of the experience that an inspector

accumulates while searching for fuel anomalies. In general, anything that is not "normal" is usually investigated in detail and is well documented with CCTV video tape, summary verbal descriptions, and photographs.

5.5.2 Poolside Inspection Aids

5.5.2.1 Binoculars

All of the fuel vendors and utilities can perform unaided and binocular-aided visual inspection during refueling outages. Simple visual inspection is used to obtain a cursory understanding of the condition of almost every viewable aspect of the reactor core. The main optical task is the identification of abnormal conditions, whether it is heavy crud sloughing or damaged reactor core hardware.

Although binoculars can provide a good cursory view of a fuel bundle, the image quality will not be as good as that from a periscope or CCTV because of the water path between the observer and the inspected surface. While all aspects of color and parallax are present, there is no convenient method to record the pictorial data, so more sophisticated inspection tools are used in detailed poolside inspections.

5.5.2.2 Closed Circuit Television (CCTV)

All of the fuel vendors and utilities that perform poolside visual inspection use or have used CCTV systems. Most of the fuel vendors use CCTV in their major fuel inspection and employ a device installed at the spent fuel pool to manipulate the fuel or the CCTV system (for examples, see Refs. 24-28). Four fuel vendors make full use of black and white CCTV and video recording systems with their inspection hardware. One fuel vendor uses CCTV and video tape exclusively in both their special fuel bundle inspection stand and their special fuel rod inspection stand. The CCTV system is equipped with variable magnification and supported with resolution charts (and sometimes a dummy fuel bundle segment) to aid in maximizing the system. The setup and use of CCTV systems is, in general, subjective and depends on the operators. No clear advantage of either design approach exists, with the exception that the less fuel is handled, the less chance there is for damage or error due to handling.

One of the vendors has two special poolside inspection stands, one small and one large, for fuel bundle and fuel rod inspection. Fuel bundle visual inspection can be performed with their small stand, which attaches to a spent fuel rack and uses a CCTV system. The TV camera can be rotated 360° around the fuel bundle while the spent fuel storage pool crane raises and lowers the bundle. This provides a quick, detailed inspection with a minimum of hardware installation but requires the use of the storage pool crane for fuel handling. All other inspection systems are independent in the sense that they only need assistance in filling their fuel bundle storage positions but can then handle fuel without the pool hardware assistance.

One vendor has a similar inspection system that uses a boom-mounted CCTV system with a pan and tilt head that can examine fuel held by the pool transport crane or be used to assist their installed inspection hardware. Inspection hardware has been designed with movable or stationary CCTV systems requiring stationary or movable fuel handling, respectively. The fuel bundle is rotated by a special turntable setup in the storage pool. Their fixture for inspecting single fuel rods can disassemble or assemble a fuel bundle and rotate or translate fuel rods independently.

One fuel vendor does not routinely make visual fuel inspections as their primary assessment of fuel condition is through sipping. That vendor indicated that CCTV resolution, in comparison to that of other optical systems (e.g., large-aperture periscopes or borescopes), is not sufficient for their poolside campaigns.

5.5.2.3 Periscopes

Most of the fuel vendors have employed periscopes in some of their fuel inspections. For one vendor, a periscope is the only acceptable viewing aid that can give them the necessary resolution and the added visual key of color for fuel rod and fuel bundle surfaces. Another vendor has used a periscope (1.5X magnification) and color film extensively in fuel rod inspection (Ref. 29). Self-developing film offers a quick assessment of photographic image quality to optimize the photograph's color and detail. The main advantages expressed by this fuel vendor for the periscope are color and resolution, with color being important in crud pattern and thickness studies.

5.5.3 Poolside Inspection Data and Calibration

The main motivation for detailed visual inspection appears to be to "locate anomalies" in the fuel bundle and fuel rod structures. In a typical inspection where CCTV is used, the entire inspection process is recorded on video tape along with verbal comments by the operating technicians. Anomalies are identified and the records sent to fuel experts for futher analysis. With periscope supported CCTV inspection, a full color record of the anomalies is made. The usefulness of color appears to hinge on whether or not a detailed crud analysis is being made. Color has been assessed as important in crud analysis by several fuel vendors. Specific visual inspection guidelines are not given for normal inspections, except when evaluating the performance of a new fuel bundle design or assessing a particular problem, such as fretting. Because of the critical timing in a reactor outage, the bulk of the data analysis (with the exception of major problems on fuel bundles scheduled to be reloaded into the core) is done after the outage is completed. The experience of the poolside inspection technicians is the "standard" for almost every aspect of visual inspection, including the definition of "anomalies," because of the subjective nature of visual inspection. An important point is that their experience is upgraded through discussion with fuel designers and in the postanalysis of the inspection data.

A summary of the data gathered from the fuel vendor's visual inspection techniques is shown in Table 5.1. The inspection of a given group of fuel bundles is usually directed by an overall guideline that identifies the fuel to be inspected and the responsibilities of the inspection team and utility personnel to complete this inspection. Fuel inspection is generally not a high priority item in a reactor outage, and some scheduled minor visual fuel inspection tasks may be altered or deleted if time for completion may make those visual inspections a critical path item. Most fuel vendors agreed that visual standards would be helpful in setting up and maintaining visual inspection hardware. However, the pattern of relying on the technician's experience persists throughout the industry, as noted by Table 5.1. No fuel inspector addresses water clarity or illumination directly; changes in illumination or image quality decisions are made based on the operator's subjective judgment. Color

TABLE 5.1. Summary of Data on Visual Inspection Techniques and Standards

Visual Inspection Item	Data From Fuel Vendors				
What Visual Standard Is Used	Experienced Technician	Experienced Technician	Experienced Technician	Experienced Technician	Experienced Technician with Test Patterns and Dummy Fuel Segments
What Is Basis for Inspection Procedure	Anomalies	Documented Procedure	General Guide and Operator's Judgment	Detailed Inspection Plan	General Guide and Operator's Judgment
How Important Is Color	Minimum	Very Important in Crud Evaluation	Important	Very Important	Minimum value
What Color or Illumination Standards Are Used	None	None	None	None	None
What Method Is Used for Recording Data	CCTV Video Tape with Verbal and Written Comments	CCTV Video Tape and Color Photographs with Verbal and Written Comments	Color Photographs with Written Comments	Color Photograph with Written Comments	CCTV Video Tape with Verbal and Written Comments

standards are not used, but special film processing of self-developing film may be used to reproduce the image color as closely as possible.

5.5.4 Poolside Inspection by Fuel Vendors and Utilities

The bulk of the detailed poolside visual inspections are done by the fuel vendors. The fuel vendor's visual inspection needs are generally motivated by their fuel codes and fuel designs. All of the utilities can perform cursory visual inspections with the aided and unaided eye; such inspections are routinely performed at PWR refueling outages and are conducted at some of the BWR refueling outages. Utilities are interested in poolside visual inspection for checking fuel bundle conditions that may be associated with reactor operation anomalies and for fuel warranty reasons. One nuclear power station with PWRs has detailed visual inspection equipment, including a CCTV and periscope; the associated utility is one of the few with such equipment (Ref. 30). Because they are seeking fewer fuel abnormalities, their attention in visual inspection is now focused on crud deposits and much smaller anomalies than in the past. Some of the utilities that were visited are planning to procure CCTV and periscopes to aid in their cursory visual inspections. The CCTV video tape record has been found valuable in later detailed analysis of fuel inspection data.

5.5.5 Visual Inspection Keys and Standards

To assure continuity in the inspection of fuel system components, one would expect to find a well-documented set of visual inspection standards or visual keys. This is currently not the case in the nuclear fuel industry. Visual inspection is subjective in nature and therefore the inspection standards or problem indicating keys are also subjective. In most cases, a visual inspector is guided by his accumulated experience and the general visual key expressed as "anomalous" or anything that is not normal. In visual inspections of fuel, there are sometimes general guidelines to help focus the technician's attention to a particular problem or fuel structure area. The technician's picture of "normal" fuel is usually constantly upgraded in the postexamination data analyses and reviews with fuel and reactor design engineers. Previous poolside visual inspection data are also available for review to help a technician understand what to expect at a particular reactor site.

In general, almost all other current poolside main fuel bundle and fuel rod visual inspections include the following:

- gross physical integrity check
- general cursory dimensional/mechanical check for such things as rod bow (fuel rod-to-fuel rod spacing) and spacer grid conditions
- checking for fuel bundle damage, such as fretting (e.g., from fuel rod vibrations caused by cross flow) and damaged spacer grids
- checking for fuel rod degradation and for cladding flat spots, corrosion, hydriding, and cracks
- checking for crud (condition and pattern) on fuel rods and bundles.

A change in gross physical integrity (e.g., missing and/or damaged components) is the easiest visual key to detect. As the visual key becomes smaller, it can be very difficult to detect, depending on its location within a fuel bundle.

The presence of pinholes in the cladding of fuel rods is very difficult to detect with visual inspections. Emitted bubbles are sometimes a good indicator of pinhole-size cladding penetrations (although the pinhole may be small enough that it does not permit water to enter a fuel rod). With failed fuel, circumferential cracks in the cladding are very rare; axial cracks are much more common. These defects by themselves are very difficult to locate in a fuel bundle. Other visual keys, such as subtle surface color or contrast changes, are sometimes helpful in locating these conditions. For example, cladding surface discolorations are very helpful in locating a hydrided area, which in turn may help visually locate a cladding penetration. The crud color has also been used to estimate the crud composition.

5.6 Environmental Limits

Because of the subjective nature of visual inspection, quantifying the environmental limits is not possible. However, we can discuss some limitations in a qualitative manner and look at the basic limits of the optical elements and human eye related to a visual inspection task.

The human eye is not a perfect imaging system with infinite resolution, as indicated by the average human eye response parameters in Table 5.2. By average, we mean the capabilites of a particular person can be slightly better or worse, depending on the individual's age, training, or experience factor; fatigue level; and fit of corrective lenses. The parameters that particularly affect poolside visual inspection are visual acuity, motion detection, and illumination level for optimum visual acuity and grey level differentiation.(a)

TABLE 5.2. Average Response of the Human Eye

Visual Acuity (Ref. 31)	One arc min
Field of View (Ref. 31)	70^{o} 160^{o} horizontally
Stereoacuity (Ref. 31)	30 arc sec (minimum difference between two angles of convergence which indicates object depth)
Focal Depth (Ref. 32)	Near point - 254 mm (10 in.) Far point - infinity
Motion Detection (Ref. 32)	Detection limit 10 sec arc Minimum - 1-2 min arc/sec Blur - 200^{o}/sec
Minimum Illumination for Optimum Visual Acuity and Contrast (Ref. 33)	323 lumen/m^2 (30 lumen/ft^2)
Usable Dynamic Range (Ref. 32)	0.318 - 31800 cd/m^2 (0.1 - 10^4 milli-Lamberts) (approximately moonlight to bright sunlight)
Minimum Detectable Brightness Difference (Ref. 32)	0.2^{o} (room light conditions)
Fovea (acute vision area)	0.3 mm diam (1.7^{o} angle from the eye principal plane)

(a) By grey level differentiation, we mean the ability to detect small differences in image intensity levels (i.e., grey levels).

The objective of a poolside inspection optical tool (binocular, periscope, or CCTV) is to optimally transmit all of the image qualities that are required by the observer to make a correct, interpretive (subjective) judgment. The most efficient and cost-effective optical system should not produce more accuracy than necessary to complete an inspection task, nor should it be lacking in any area that would reduce the reliability of the interpretation. High resolution in a visual imaging tool is desired when either a secondary image is to be recorded or enlarged or when vernier acuity (ability to read the displacement of two parallel butted lines as in a micrometer vernier) is required.

The human eye is an extremely poor photometer; it is very inaccurate in judging absolute levels of brightness. However, the eye is excellent if one must judge or match, to a high degree of precision, relative brightness and color of two closely adjacent areas. This ability is lost as the separation between the two areas of interest is increased. Color can help make an image easier to read if the viewer is not familiar with an image; however, color is not a help for the trained eye that can see a small detail within an apparently "poor" or "cluttered" image. (An example of this ability is the rejection of color enhancement by X-ray and neutron radiograph technicians.)

The image response can also be degraded by the optical scattering from contaminants in the pool water. The severity of degradation depends on the illumination geometry and the density and reflectivity of the contaminants. Although there are techniques to quantify water quality, the subjective nature of poolside inspection makes the selection of an environmental limit almost impossible. To date, there are no "hard" guidelines to follow, as any guideline must be established with experimentation and numerical techniques. The guidelines must be established, keeping in mind the objective of the fuel inspection task.

Images can also be degraded in a spent fuel storage pool by thermal gradients. However, this image degradation is minimal for visual inspection of fuel in the storage pool because the fuel has cooled before being inspected. In other reactor areas where thermal gradients exist, a distorted image is probably much better than no image at all, and thermal gradients are usually considered only a minor irritant.

In most hot cells and spent fuel storage pools, there is some degree of structural vibration from the support facilities. The human eye can tolerate a certain degree of image motion and still produce a good visual response, but if the vibration amplitude and frequency exceed this threshold level, there will be a reduction in image resolution and contrast and visual response will be degraded. Photographic and TV systems do not share this same immunity. For TV, blurring is especially evident with video tape and single frame play-back viewing. To the viewer, the image motion may not be a degrading element as the human vision system integrates the moving images and provides a mental composite image with vision detail not found in any single frame. The image motion will produce an apparent improvement in the image detail and subsequent visual resolution.

The response data in Table 5.3 were prepared from available CCTV, periscope, borescope, and photographic film specifications. As technology advances, the new hardware will change some of the listed parameters. It should be pointed out that utilization of the full limits for each imaging aid is not independent of the subjective response of the viewer or method of implementation. Therefore, a direct relationship to fuel system component parameters (such as the location of a pinhole leak in the cladding of fuel rod) cannot be made.

We can make a "system" comparison if assumptions concerning the imaging systems (such a field of view) are made. Table 5.4 shows a comparison of periscope, black and white TV, and black and white film characteristics, assuming a full 70 mm film format, a 15^{o} field of view, and a one-to-one system magnification. The table indicates that there is a wide range in resolution capability for the most common poolside inspection tools (periscope and TV). It should be emphasized that good image reproduction is only one of the contributing factors in optimizing the visual recognition process for poolside visual inspection.

In poolside visual inspection, eye fatigue when using the periscope was indicated as one of the visual inspection problems. In any visual inspection task, fatigue is a factor in the maintenance of a base-line reference and overall visual sensitivity. Because of the subjective nature of this limiting factor, there are no concise ways to quantify it.

TABLE 5.3. Response Data for Typical Poolside and Hot Cell Optical Tools

System (Manufacturer, Mfr.)	Resolution	Magnification	Apparent Field of View	Dynamic Range/Sensitivity
TELESCOPE OR BINOCULAR	5.5 (clear aperture) arc sec	11X (clear)	--	
PERISCOPE (Mfr. 1's and Mfr. 2's Nuclear Periscopes)	5.25 arc sec (magnification dependent)	2-20X	30°	f/10
BORESCOPE [Mfr. 1, 44.5-30.2 mm (1 3/4-1 3/16 in.) dia]	50 arc sec - 16 arc min	1/2 - 10X	30-40°	
BLACK AND WHITE TV:				
--Radiation Resistant (Mfr. 3, Mfr. 4, and Mfr.5)	Horizontal: 600-1000 TV lines Vertical: 525 TV lines	(lens dependent)		1.076-10,760 lm/m^2 (0.1 - 10^3 foot-candles), 10 grey scale resolution
--Regular High Resolution (Mfr. 5)	Horizontal: 1200-1400 TV lines Vertical: 575-650 TV lines	(lens dependent)		1.076-10,760 lm/m^2 (0.1 - 10^3 foot-candles), 10 grey scale resolution
COLOR TV: (Mfr. 5's Single Tube)	Horizontal: 275-300 TV lines (400 TV lines in best $40,000 system) Vertical: 575 TV lines	(lens dependent)		10 grey scale resolution at 2690 lm/m^2 (250 foot-lamberts), 377 lm/m^2 (35 foot-lamberts) scene with an f/4 lens system bightness, produces a usable picture
FILM				
Black and White:				
--Mfr. 6's Self-Developing Positive/Negative Film	Neg. 150-165 lines/mm; Pos. 14-17 lines/mm			ASA 64
Mfr. 6's Self-Developing Sheet Film	20-22 lines/mm			ASA 300
--Mfr. 7's Film (70 mm rolls)	96-135 lines/mm			ASA 125
Color:				
--Mfr. 6's Film	(less than black and white)			ASA 75
--Mfr. 7's Film (70 mm rolls)	69-95 lines/mm			ASA 100

TABLE 5.4. Calculated Resolution Comparison(a)

	TV Line Resolution	Angular Resolution
70 mm Black and White Film	19,000 TV lines	6 arc sec
CCTV: Vertical	650 TV lines	166 arc sec
Horizontal	1,400 TV lines	77 arc sec
Periscope	4,300 TV lines	25 arc sec
Human Eye	----------(b)	60 arc sec

(a) Assumed Parameters:
1. Full 70 mm image format for the black and white film.
2. 15^{o} field of view.
3. Unity system magnification.

(b) Eye accommodation causes eye resolution to be angular dependent only.

Table 5.4 indicates that the periscope is capable of much better resolution than the eye and that photographic film can also record much more detail than the eye needs. Because of the subjective nature of visual inspection, one cannot make an unqualified choice as to which optical tool (CCTV or periscope) is better for poolside inspection; the real proof is not in the image quality, but rather in the proper detection of fuel bundle and fuel rod anomalies. The CCTV cannot match the resolution and dynamic brightness range available through a periscope. However, a video tape recording is possible with CCTV, and the image motion can enhance the subjective visual acuity of the human vision system, supporting an adequate inspection for a large portion of the poolside inspection problems.

5.7 Hot Cell Visual Inspection

Poolside inspection is a relatively new technology area in comparison with hot cell technology. In developing poolside visual inspection hardware, the initial approach has been to adopt existing technology, which includes some hot cell visual inspection tools. A bench mark position for judging the status of poolside inspection can be obtained by reviewing hot cell techniques. In this report, the intent is not to indicate that hot cell techniques and tools are standards or design goals for any poolside inspection system. Hot cell technology is much more established, and some of the more exotic techniques may find use in future poolside inspections.

Some examples of hot cell visual inspection installations and types of tasks are shown in Table 5.5 (Refs. 34-41). The major differences between hot cell and poolside technology are that hot cell inspection is usually not subject to the critical path restraints that affect the available poolside inspection times and that much finer inspection detail (magnified images) is required in a hot cell system. Poolside technology is largely concerned with macroproperties (physical integrity), while hot cell inspection normally includes extensive microproperty evaluation and metallography. In addition, hot cell inspection is not normally used for routine fuel rod and fuel bundle surveillance but is used in conjunction with research and development (i.e., new fuel designs and detailed analysis of anomalies in support of poolside inspections). Because optical conditions are much more controllable in a hot cell, much finer optical details can be observed and photographed. As shown in Table 5.5, most hot cell equipment is a wall-penetrating type optical system and not a CCTV unit. The periscopes and borescopes provide much greater image detail and reproduction of image color. Usually the hot cell optical system is capable of a large range of image magnification (such as a 1-25X magnification in variable or continuous steps).

The general visual descriptive keys are quite similar to those for poolside visual inspection, with the exception of the use of color. More emphasis is placed on detail and color in hot cell examinations because the objective is not to accept or reject fuel system components but to determine the cause(s) for a condition that results in acceptance or rejection.

TABLE 5.5. Hot Cell Visual Inspection

Inspection Task	Equipment	Calibration	Visual Keys
General hot cell inspection	Stereo (macroscope) periscope with stereo camera and variable magnification	1.0x mag., 1 cycle/mm resolution 15x mag., 30 cycle/mm resolution 10x mag., 55 cycle/mm resolution 15x mag., 70 cycle/mm resolution	None given
SNAP fuel element visual inspection	Wall periscope, 10x magnification, stereo microscope (up to 30x magnification)	Effective 2x magnification measured	Cladding and weld defects
Fuel rod visual inspection	Stereo periscope (up to 23x magnification)	None described	Blisters, cracks, pits, surface coloration
Visual inspection fuel rod	Stereoscopic viewer, 30x magnification	None described	Abnormalities, surface cleanliness
HTGR fuel element visual examination	Short focus binocular and in-wall periscope	25x mag., 102 cycle/mm resolution	Cracks, abnormalities, bowing
Fuel bundle visual inspection	Through-wall windows, binoculars and cameras	None described	
Fuel rod visual inspection	Stereo periscope, 5,7,14, and 40x magnification	None described	
Hot cell visual inspection	Stereo microscope 1-60x magnification with a system of lenses that can be rapidly adjusted for varying distance views while keeping the image in focus; 35 mm self-developing film type camera and stereo 35 mm camera options	Image on film is 1/7 size of viewed image	

5.8 Time and Personnel Requirements and Inspection Frequency

5.8.1 Poolside Visual Inspection Time and Personnel Requirements

Although the amount of final summarized data from a typical poolside inspection campaign may be very small, there is usually a fairly large time and personnel investment in any poolside visual inspection campaign. Because there is a wide variety in the visual inspections that are performed on fuel bundles and rods, the time and personnel requirements also vary accordingly. Time and personnel estimates for visual inspection obtained during the meetings are summarized in Table 5.6 (also see Section 4.2). The time required for a visual inspection

TABLE 5.6. Visual Inspection Time/Personnel Estimates

Data from Fuel Vendors

Inspection Task	Estimated Time	Personnel Estimate
Visual inspection of 4 sides of a fuel bundle with closed-circuit television (CCTV)	2 hours	
Detailed periscope examination	3-4 hours	
Set up and remove large special inspection stand	2 weeks	Two engineers and two technicians/ shift
Peripheral rod visual inspection	2-4 hours	
Casual inspection of 2-4 sides of a fuel bundle	2-4 hours	
Casual inspection of a fuel rod	20 minutes	
Visual and fuel rod-to-fuel rod spacing	12 hours	
Typical total inspection (all inspection tasks)		3-6 people/shift
Set up visual inspection equipment	3-4 days	
Remove fuel rods, inspect and reassemble into fuel bundle	2-3 hours	
Total detailed fuel rod examination	3 hours	
Basic CCTV inspection	(1 day for equipment setup)	One engineer and one technician/shift
Video tape 20 fuel bundles and perform fuel rod-to-fuel rod spacing (i.e., water channel) gaging on 5 fuel bundles	14 days	

of a fuel rod or bundle depends on the anomalies present and, in the case of periscope inspections, the amount of photography required. The general rule is that there is at least one experienced lead engineer (supported by 2 to 5 technicians) who is responsible for directing the visual inspection and, in most cases, is doing the actual visual inspection.

5.8.2 Frequency of Visual Inspection

During every refueling outage, the cursory visual inspection with or without binoculars is performed. The comments in Table 5.7 on poolside visual inspection frequency came from the discussions at the meetings with the fuel vendors.

TABLE 5.7. Poolside Visual Inspection Frequency

Comments from Fuel Vendors			
In a typical poolside inspection by one vendor involving 15 fuel bundles, all would be visually examined and additional measurements taken as desired.	One vendor indicated that with a very detailed poolside inspection, including fuel bundle disassembly/reassembly, one fuel bundle might be inspected per outage.	A major inspection (including detailed visual) is made by one vendor at about 10% of the refueling outages.	Of the 20 or so refuelings done per year, about three to four are selected by one vendor for inspection beyond normal binocular visual inspection.

5.9 Summary and Conclusions

Visual inspection is normally a very tedious, subjective task--so much so that in some cases very general inspection guidelines are given (e.g., in the inspection for anomalies) with results recorded in very general generic terms, such as "the crud is light to moderate."

5.9.1 Visual Inspection Comparisons

In comparing poolside visual inspections, the following conclusions can be drawn:

- The visual keys used in a visual inspection task are generally gross fuel bundle integrity and the spotting of anomalies in or on the fuel bundle or its components (fuel rod, spacer grid, etc.).

- The importance and role of visual inspection does not have a complete uniform emphasis throughout the nuclear fuel industry. A contributing factor to this lack of uniformity is the variation of experience; however, this lack of uniformity is also partially due to the uniqueness of each reactor outage and differences in fuel designs and their performances. For example, at a BWR, the main inspection tool is sipping (with visual inspection used as a verification tool), while at a PWR, visual inspection may typically be the only poolside inspection performed. The inspection during an outage will receive more emphasis if anomalous reactor operation has been experienced or if a fuel system design change is being studied.
- The basic visual standard for the poolside visual inspection task is a trained and experienced inspection engineer. As the visual inspection task is considered highly subjective, no "book of standards" appears to exist. However, equipment and procedures for visual inspection are usually well documented as unpublished data (these are usually the proprietary property of the fuel vendor or utility). With the "human" visual standard, there is a learning curve for anyone newly introduced into the poolside visual inspection program.
- There is not uniform agreement on what are the best types of visual tools and equipment for poolside inspection. Proponents of periscope systems claim that black and white TV does not have enough resolution to see the fine detailed anomalies present in modern fuels and that color is a very important inspection factor. Some inspection campaigns use TV alone, others use TV with periscope backup for the finer inspection detail and for color evaluations, and, finally, some poolside inspections are done with periscope only. It should be emphasized that the end readout from the optical tool is the human visual system, which is highly subjective. Training and experience can add a broader dimension of clarity to a picture that appears to lack definition or resolution, especially when the image is moving and can be manipulated. Therefore, there appears to be no clear

choice for either CCTV or periscope systems in the poolside visual inspection. The best approach, of course, is to use the advantages from both systems.

5.9.2 Failed Fuel Comments

The value of poolside visual inspection in detecting failed fuel is affected by several factors, including the limited visibility of fuel rod surface areas in a fuel bundle, the subjective nature of the visual inspection process, and the time available for fuel inspection. Some prior knowledge, such as the fact that fuel rods with higher duty cycles have a greater probability of failing during reactor operation, can be useful in any visual (or other) inspection program. Visual inspection is not a primary tool in the detection of failed fuel. Fuel vendors and utilities consider visual inspection at best a very poor technique for even verifying which fuel rods from a fuel bundle, flagged as a leaker by sipping, are leaking. Small cladding cracks and perforations can be very difficult to see, although pinholes can be seen if bubbles are being emitted during the visual inspection. One fuel vendor estimated that of those fuel rods ultimately determined to be failed, probably only 10% or less are detected by visual inspection of the fuel bundle. Only a small percentage of the total surface of the fuel rod is visible in a fuel bundle that is not disassembled, which makes the identification of a leaking fuel rod difficult even when a large perforation or discoloration is present.

6. GAMMA SCANNING

6.1 Introductory Comments

Gamma scanning is the point by point measurement of the gamma emission rate from a radioactive object. The term is generally applied to the incremental measurement of the activity along the axis of an irradiated fuel rod or fuel bundle. Data from a gamma scan consists of measured activities for selected isotopes at specific points along a fuel rod or bundle. In practice, a radiation detector is positioned in such a manner that it can receive gamma radiation only from a limited area along the axis of a fuel rod or bundle. The device employed to limit the radiation received is called a collimator and consists of a small air-filled hole (approximately 0.25-cm in diameter) in a massive shield. The fuel rod is moved incrementally or continuously past this hole to obtain a record of radiation intensity as a function of axial position.

Gamma scanning has been performed for over 15 years and is currently used as a poolside inspection technique to assess the performance of commercial nuclear fuels. The purpose of this report is to describe gamma scanning of fuel rods and fuel bundles from power reactors with regard to function, cost, complexity, etc., and to contrast poolside measurements with measurements made at hot cell installations.

6.1.1 Uses of Gamma Scanning

Gamma scanning is performed to meet two general objectives: (1) neutronic measurements on the fuel and (2) metallurgical measurements on the fuel and cladding. Neutronic measurements are related to the power history of the rod or bundle and are used for such things as qualification of neutronic calculation codes, burnup measurements, and examination of the reactor power distribution. Neutronic calculation codes have often been verified by the destructive examination of selected fuel rods. Gamma scanning permits the measurement of several fission products without the expense of destructive examinations. The measurement of short-lived isotopes can provide information on the power distribution over the whole core or within a fuel bundle, while measurements on a long-lived isotope permit the determination of total fuel burnup or of relative burnup as a function of position in the reactor core.

Absolute burnup measurements can be performed with an accuracy of about five percent under a fixed set of conditions of irradiation and with a calibration tailored to these conditions. In one case with MTR fuel, comparison of gamma-counting-determined burnup with declared burnup data has shown agreement with a precision of 2.1% at the one sigma level (Ref. 42) using the $^{134}Cs/^{137}Cs$ ratio. If the measurements are attempted with another set of fuel pins with a different irradiation history, the accuracy will be about ten percent. If the safeguarding of nuclear material receives more attention in the future, one of the possible results could be that all inventories of fissionable materials might have to be verified by measurements. Gamma scanning at poolside would be a major technique for inventory verification of spent fuels.

Metallurgical measurements from the examination of the fuel and cladding provide information on such things as fuel integrity and fuel swelling or densification. Densification is seen as an overall shrinkage of the fuel column or the occurrence of gaps between fuel pellets. Such conditions are readily detected via gamma scanning since the intensity of the characteristic gamma radiation from the fuel will change at gaps in the fuel column or at the end of the fuel column. Figure 6.1 shows an example of a gamma scan along the axis of a fuel rod and indicates some of the features one might expect to observe. Apart from radiography, gamma scanning is the only technique that provides direct information on the fissile material condition. The use of small collimator apertures permits resolution of small defects in the fuel.

A new technique (computerized tomography) that has been used in a hot cell permits the measurement of the cross-sectional distribution of fission products in the fuel (Ref. 43). By scanning across a diameter of a fuel rod with a small hole (diametral scan) at one elevation, it is possible to obtain a projection of the activity in a cross-section of the fuel. Repeating this process at several angular orientations provides a number of projections of the activity in the same cross sectional area. The inverse mathematical transformation of these projections will reconstruct the distribution of the activity within a given cross section. Several algorithms, which rely heavily on

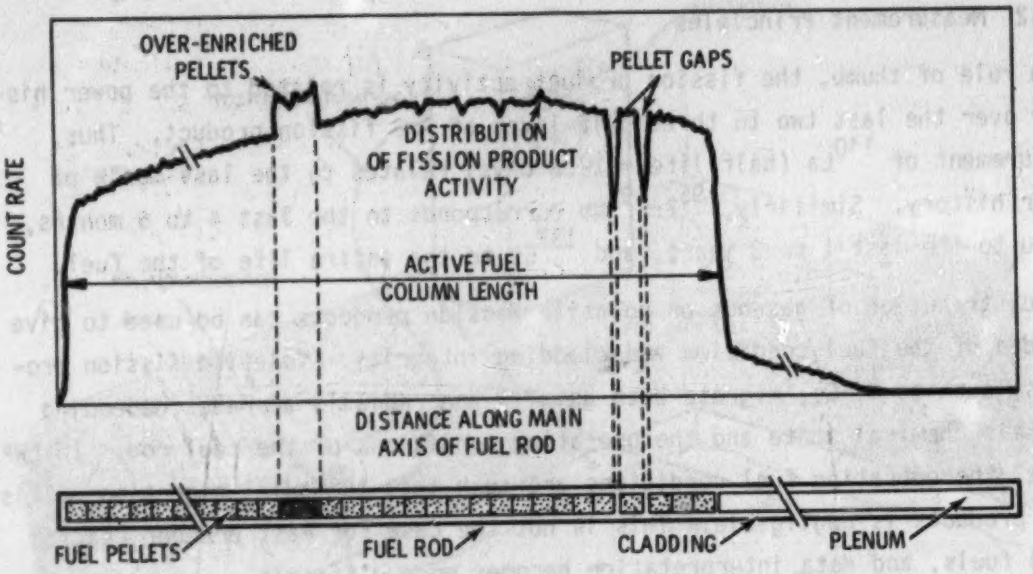


FIGURE 6.1. Simulated Gamma Scan Along the Main Axis of a Fuel Rod (The overall curve indicates total burnup in the case of a long half-life fission product such as ^{137}Cs, while for a short half-life fission product such as ^{140}La, it is related to the recent power distribution).

modern high-speed computation techniques, have been developed to implement this type of reconstruction. Computed transverse axial tomography, as this technique is known, has been applied to several disciplines, but the most notable application is in medicine, where the technique has revolutionized the radiographic analysis of human disease.

Gamma scanning of fuel rods or fuel bundles at poolside for commercial reactors is generally limited to simple measurements of fuel condition. Scans are used to detect gaps in the fuel, fuel densification, or fuel swelling. Currently, one fuel vendor is working on a poolside gamma scanning program that involves the measurement of power distribution at several reactors (Refs. 44 and 45). This program is under the sponsorship of the Electric Power Research Institute (EPRI) and departs from the normal gamma scan campaigns of fuel vendors due to its large magnitude and the use of results. The data generated in these measurements can be used to benchmark neutronic calculation codes, whereas this is generally done via destructive analysis of selected fuel rods.

6.1.2 Measurement Principles

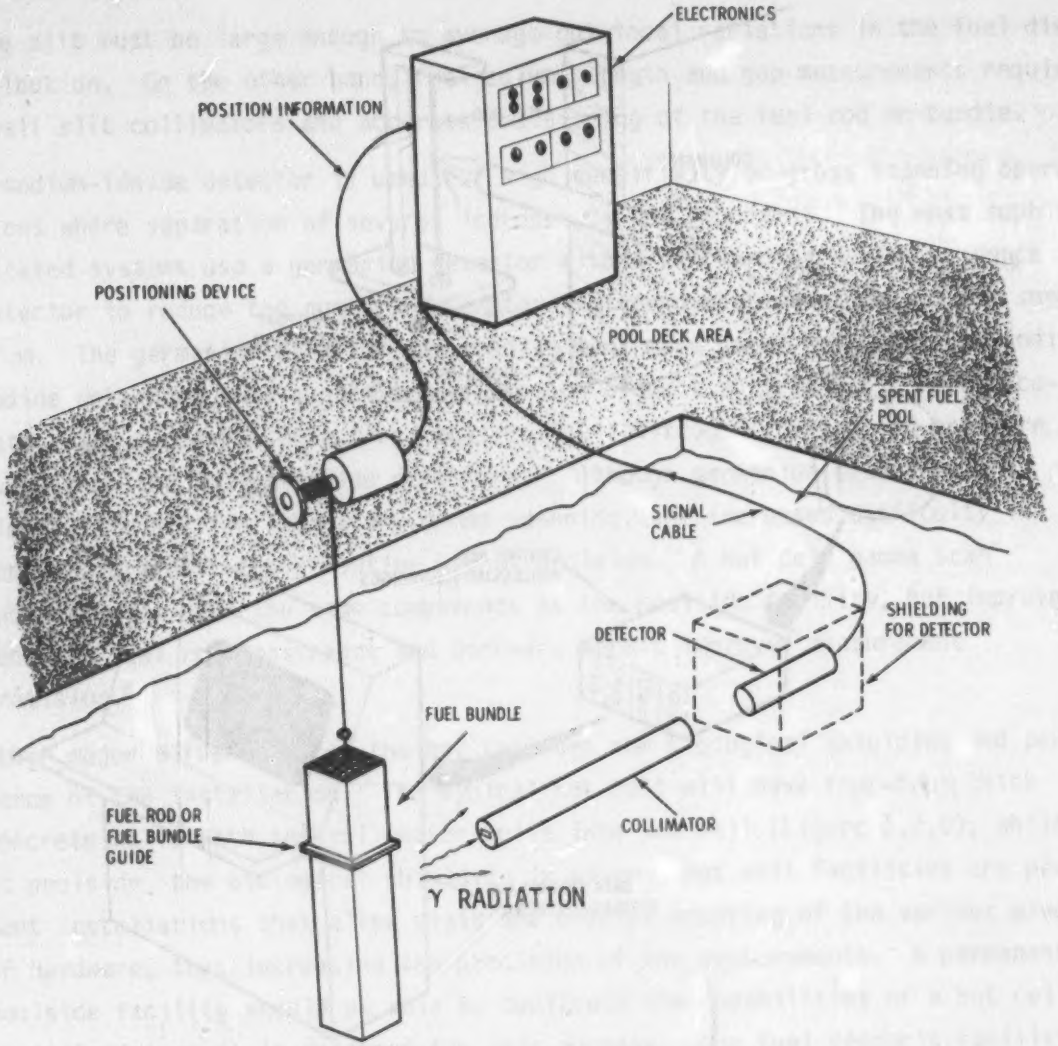
As a rule of thumb, the fission product activity is related to the power history over the last two to three half-lives of the fission product. Thus, measurement of ^{140}La (half life = 12.8 days) relates to the last month of power history. Similarly, ^{95}Zr-^{95}Nb corresponds to the last 4 to 6 months, ^{106}Ru to the last 1 to 2 years, and ^{137}Cs to the entire life of the fuel.

The distribution of gaseous or volatile fission products can be used to give an idea of the fuel condition and cladding integrity. Volatile fission products, such as ^{137}Cs, migrate both axially and radially at rates depending on their chemical state and the operating conditions of the fuel rod. In LWR fuels, the operating fuel conditions are such that the axial migration of fission products is negligible. This is not the case for Fast Breeder Reactor (FBR) fuels, and data interpretation becomes more difficult.

6.1.2.1 Measurement Hardware

Gamma scanning can differ in sophistication from a simple manual system to a highly automated system operating under software control. The poolside inspection systems are generally quite simple; however, most gamma scanners have several pieces of hardware in common, although the exact implementation of the hardware can differ greatly.

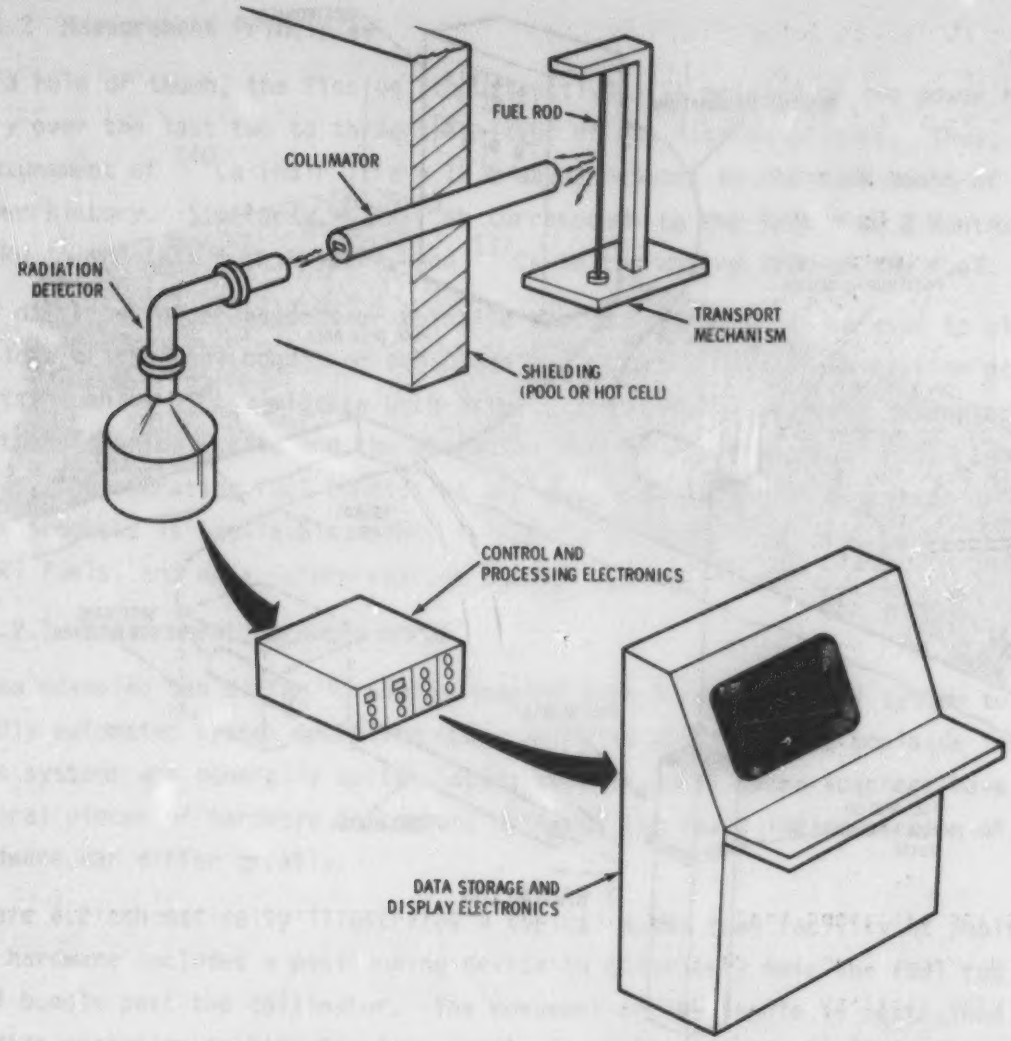
Figure 6.2 schematically illustrates a typical gamma scan facility at poolside. The hardware includes a positioning device to accurately move the fuel rod or fuel bundle past the collimator. The movement of the bundle is restrained by a guide mechanism to keep the fuel bundle in position with respect to the collimator as it is moved vertically. The collimator has apertures to select the area viewed on the fuel bundle or fuel rod and will often have a variable attenuator (filter) to control count rate. At the opposite end of the collimator, the collimated beam of activity interacts with a radiation detector to produce an electrical signal. This signal is carried via cables to the electronics located in the deck area around the pool. The electronics will record the gamma activity as a function of position on the fuel bundle or rod. Simple systems will use a chart recorder synchronized with the translator to



(a) Schematic Illustration of Gamma Scan Facility at Poolside

FIGURE 6.2. Typical Gamma Scan Facilities

record the information. The more sophisticated systems use computers to record the data, control translation of the fuel bundle or rod, and perform data analysis.



(b) Gamma Scan Facility at Poolside or Hot Cell

FIGURE 6.2. (contd)

A narrow slit collimator, which implies high spatial resolution, is not always desirable. Measurement of power distribution is often performed by making measurements at selected points along the fuel rod or bundle. In this application,

the slit must be large enough to average out local variations in the fuel distribution. On the other hand, fuel column length and gap measurements require small slit collimators and accurate positioning of the fuel rod or bundle.

A sodium-iodide detector is used for high sensitivity or gross scanning operations where separation of several isotopes is not important. The most sophisticated systems use a germanium detector with a surrounding anticoincidence detector to reduce the number of Compton-scattered photons stored in the spectrum. The germanium detector can resolve many more gamma rays than the sodium iodide detector; thus separation of fission product activities is more accurate. The germanium detectors require liquid nitrogen cooling and are more bulky than the sodium-iodide detectors. Although germanium detectors are almost standard for laboratory gamma scanning, the increased difficulty in handling prevents their routine use at poolside. A hot cell gamma scan facility will have the same components as the poolside facility, but improvements in fuel rod constraint and hardware permit improved measurement precision.

Other major differences at the hot cell are the biological shielding and permanence of the installation. The typical hot cell will have four-foot thick concrete walls with the collimator built into the wall (Figure 6.2,b), while at poolside, the biological shielding is water. Hot cell facilities are permanent installations that allow rigid and precise mounting of the various pieces of hardware, thus increasing the precision of the measurements. A permanent poolside facility should be able to duplicate the capabilities of a hot cell installation if it is designed for this purpose. One fuel vendor's facility at a nuclear power station with PWRs is essentially permanent, but it is not designed to duplicate hot cell capability.

6.1.2.2 Data Reduction

For simple detection of length of and gaps in the active fuel column, a record of the gross activity correlated with fuel rod position will suffice. Often a chart recorder plot of the gross activity is used with a known relation between chart speed and rod/bundle motion. Measurement of power distribution or burnup requires accurate measurement of selected isotopes and correction for such

parameters as decay, dead time, background, filters, etc.[a] Often the data are recorded at the measurement site and analyzed at a central computer facility, but the growing sophistication of minicomputer systems permits most of these analyses to be done concurrently with data collection. The corrections introduce an error of 3 to 5%, which limits the accuracy of measurements.

At the high count rates common at poolside, corrections for dead time[a] as high as a factor of approximately 2 can be required (Ref. 45). Thus the error associated with the correction becomes significant.

6.2 Poolside Gamma Scanning

6.2.1 Introductory Comments

Gamma scanning is not specifically sensitive to a breach in the fuel rod cladding and thus is not directly useful in locating the failure site(s) on a fuel rod as long as we define failure as a breach in the integrity of the cladding. The major use of gamma scanning at poolside is to examine the active fuel column of a fuel rod for axial length and for gaps. Early in power reactor experience, fuel densification was an important problem and, in some cases, led to collapse of fuel rod cladding. At that time, measurements via gamma scanning were very important in the assessment of fuel performance. Subsequently,

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(a) Terminology is identical with that of nuclear counting and complete definitions or discussions can be found in several texts (see Refs. 46 and 47). Brief explanations of some terms are given below:
Decay - Counting of short half-life isotopes requires normalization of various counts to a common time for valid comparison of activity.
Dead Time - For all counting systems, a minimum time interval of separation for two consecutive events exists for the events to be recorded separately. Events arriving in this interval (dead time) are not recorded, and the fractional loss increases with count rate. Comparison of count rates requires a correction for dead time.
Background - The count rate in the energy interval of a selected gamma energy will include contributions from other events, including Compton-scattered gamma rays from higher energy gammas and contributions from other sources in the general environment. Algorithms exist that permit stripping a selected photopeak from its background continuum with an accuracy of 3-5%.
Filters - Lead pieces are often introduced into the beam to lower the count rate from a fuel rod (control dead time). Attenuation by these filters must be corrected during analysis.

the fuel vendors have gained an understanding of the causes of densification and have largely corrected the problem. Gamma scanning is now used for post-irradiation examination of new fuel designs to verify that the fuel is performing as designed with regard to densification. An exception is the current EPRI-sponsored campaign by one vendor to examine the lanthanum-140 in various types of power reactor fuels and obtain information on the recent power distribution within these reactors. The data collected is to be used to qualify various reactor core simulator codes.

6.2.2 Type of Measurements

Table 6.1 shows the types of measurements currently made at poolside with gamma scanning systems. The table shows the purpose of the measurements and whether the measurements are made on rods or bundles. The frequency of poolside gamma scan measurements is low and several fuel vendors have not made gamma scan measurements at poolside for several years. One fuel vendor considers gamma scanning to be a physics (neutronics) tool and makes measurements at a hot cell on selected fuel rods. Although that vendor does not feel gamma scanning is a poolside inspection problem, they recommend gamma scanning beam ports for their spent fuel pools and some of their reactors have such ports. That vendor also is currently performing poolside measurements to determine power distribution. Another vendor has not performed any poolside measurements since their initial efforts at two PWRs about seven years ago. The other vendors have made measurements more recently; however, the dates of these measurements were not obtained.

TABLE 6.1. Measurements Made Via Poolside Gamma Scanning

Variable	Measurements Made By Fuel Vendors[(a)]				
Pellet Gaps/Interface	X	X	X		X
Active Fuel Column Length	X	X	X		X
Burnup Profile			X		
Power Distribution			X	X	

(a) One fuel vendor is performing a series of gamma scan measurements under EPRI contract which are not part of their poolside inspections.

6.2.3 Measurement Hardware

Table 6.2 compares the hardware used by the various fuel vendors. Gamma scan facilities were purchased by two fuel vendors from the same manufacturer and are very similar; however, the other systems are quite diverse in both design and implementation. Another fuel vendor uses both a sodium-iodide and a germanium detector system in their gamma scanning, and their systems are by far the most sophisticated in use at poolside and the best documented (information on references transmitted to the NRC).

The selection of the detector is important if separation of isotopes is desired. A solid-state detector such as Ge(Li) allows ready identification of all the gamma emitting fission products, while the classic sodium-iodide detector only allows separation of major energy groups (i.e., ^{140}La, 1596 keV; ^{95}Kr-^{95}Nb, 724+757+766 keV). The Geiger-Müller (GM) counter does not allow any energy discrimination and will respond to all gamma energies, including the low-energy scattered photons. For simple gap identification and fuel column length measurements, energy discrimination is relatively unimportant.

The end use of the results dictates the selection of the collimator width and scan speed. Large collimator widths and high scan speeds will mask small changes, such as normal pellet-to-pellet gaps, but will be sufficient for relative fuel column length measurements. On the other hand, very small collimator openings will reduce the count rate so much that long count times or long time constants will be required to reduce statistical fluctuations. In turn, this will require slow scan rates. The fuel vendors use similar collimator sizes and scan rates, as noted in Tables 6.2 and 6.3, respectively; however, one fuel vendor is an exception because they employ a large collimator to view a cross section of an entire assembly. This procedure prevents sensitivity to small anomalies that could bias the power distribution measurements.

The mechanical system, including the transport and restraint mechanism, must keep the examined object (fuel rod or bundle) in front of the collimator and move it at a constant, measured rate. Lateral movement of the object will vary the observed count rate due to changes in the path length and geometry. Axial interpretation of the counts requires accurate positioning in front of the collimator.

TABLE 6.2. Comparison of Hardware Used at Poolside

Hardware Type	Data from Fuel Vendors				
1. Detector	NaI	NaI	NaI	NaI, Ge(Li)	Dual GM counters
2. Beam Filter, mm (in.)	None	Yes	12.7 (0.5)	38.1 (1.5)	None
3. Collimator Slit Size, mm (in.)	Variable, 0-7.6 (0-0.3); 2.54 (0.100) typical		1.57x12.7 (0.062x0.5)	14.0x216 (0.550x8.5); 2.54x216 (0.100x8.5)	0.508 (0.020)
4. Fuel Bundle/Rod Restraint	Rollers	Basket	Guide tube	Suspended or Basket	--
5. Axial Motion	Overhead crane	Fuel Bundle Elevator	Separate Winch	Fuel Bundle Elevator	Separate Transport
6. Data Readout or Storage[a]	RM	RM	RM	RM, MCA Computer	RM

(a) RM = Ratemeter and Chart Recorder; MCA = Multichannel Analyzer

6.2.4 Measurement Results

Table 6.3 shows measurement results from poolside gamma scanning by various fuel vendors. Results are relatively similar, with the best resolution and length accuracy shown by the companies using the smaller collimators and slower scan rates. The accuracy and precision values shown on Table 6.3 are not directly comparable since methods used in arriving at these numbers varied between fuel vendors. In some cases, the accuracies appeared to be an estimate on the part of the given fuel vendor; in other cases, they represent a precision (repeatability) from a series of measurements.

In general, the fuel vendors collect data from fuel rods. Even when fuel bundles are scanned, the collimator is aimed at a corner fuel rod, which limits the counting to the four corner rods. Fuel vendors having fuel bundles with removable fuel rods can examine a greater number of the rods.

6.2.5 System Standardization

Standardization of a gamma scan system is important if results are to be used for more than simple qualitative assessments on an individual fuel rod. The simplest standardization (calibration) is repeated counting of a standard source. Two fuel vendors hold a single rod or bundle in reserve that they recount periodically to "standardize" their counts. This is a simple and accurate method of detecting problems.

Standardization or calibration of the axial length traverse is also important. This is normally done by calibration of the traverse rate of the scan mechanism and calibration of chart speed. One fuel vendor has a fairly elaborate technique to calibrate the axial scan of corner rods of fuel bundles. The chart recorder drive is synchronized to an optical encoder on the hoist. Distance on the chart is calibrated against fluctuations in the count rate caused by the spacer grids on the fuel rod. The true location of the spacer grids is determined by visual readings from a stretched scale.

6.2.6 Logistic Requirements

Poolside gamma scanning space and cost requirements are hard to estimate from information furnished by the fuel vendors since in most cases the information

TABLE 6.3. Measurement Results from Poolside Gamma Scanning

Parameter	Data From Fuel Vendors				
Fuel System Component Measured	Bundles[a]	Bundles[a]	Rods and Bundles	Rods and Bundles	Rods
Isotopes	Gross (>0.3 MeV)	^{95}Zr-^{95}Nb	^{140}La, ^{95}Zr ^{95}Nb	^{140}La, Several	Gross
Position Accuracy, mm (in.)	0.762 (0.030)	6.35 (0.250)	Resolution is 5.08 (0.200)	±5.08 (±0.200)	±1.52 (±0.060)
Scan Rate, mm/min (in./min)	25.4-76.2 (1-3); 35.6 (1.4) typical	102(4)	305-406 (12-16); 25.4 (1.0)[b]	Discrete Points	0-2440 (0-96); 63.5 (2.5) typical
Gap Resolution or Precision, mm (in.)	~2.54 (~0.100)		~1.52 (~0.060)	(c)	± 0.142 (±0.0056)
Length Accuracy, mm (in.)	5.08 (0.200)	6.35 (±0.250)	1.27 (±0.050)	(c)	±0.660 (±0.026)
Count Repeatability			±20% at two sigma level		
Typical Scan Time for One Fuel Bundle	360-480 min	60 min + handling	60 min + handling	60 min	30 min + handling

(a) Scanning of corner fuel rods in the fuel bundle.
(b) Slower speed required to see pellet interfaces.
(c) Not applicable

was available only for the integrated poolside inspection system. For two fuel vendors, the gamma scanning system was a part of a larger poolside system and required an estimated 27.9 m^2 (300 ft^2) of pool space and about 18.6 m^2 (200 ft^2) of deck area. Setup time was on the order of 30 to 42 man-days for according to one of those fuel vendors.

Three fuel vendors each had separate gamma scan systems. Each system required about 2.79 m^2 (30 ft^2) of pool area and an estimated 9.29 m^2 (100 ft^2) of deck area. Setup time for one of those vendor's system was about 2 man-days while another of those vendors quoted about 30 man-days.

Gamma scanning requires support from the utilities (e.g., to move fuel bundles, provide power, etc.) similar to that needed for the other inspection techniques. The only unusual support requirement is liquid nitrogen for the solid-state detectors used by one fuel vendor.

6.2.7 Analysis of Poolside Data

In general, the personnel involved in collecting the data at poolside for gamma scanning do not analyze the data. Operations at poolside are primarily for data gathering and involve only a cursory examination of the data for anomalies. The collected data are recorded on charts or in a few instances on magnetic tape and sent back to the fuel vendor facility for analysis by the fuel analysts. A major use of the data is to determine the overall fuel column length from the scans and in turn use this information to determine the degree of fuel densification or swelling. This can be done simply by scaling the available fuel rod scans. In many instances, the same fuel bundles or fuel rods will be followed through three reactor cycles so the densification or swelling can be analyzed as a function of fuel burnup.

A measurement campaign currently underway by one fuel vendor analyzes the data for power distribution. The data are collected on magnetic tape and sent back to the central facilities for analysis. Corrections are made on the data for such things as decay of the isotope and count rate. The high gamma count rates present at poolside during gamma scanning make it mandatory that the investigators pay attention to count rate effects. High count rates can cause losses and can cause shifts in the spectrum if a spectrum is accumulated. For many

of the qualitative examinations this is not important; however, if one wants to examine power distribution, even on a relative basis, it is important that the information be corrected for all count rate effects and decay so each point will have an equivalent weighting.

6.2.8 Future Poolside Capability

With a properly designed gamma scan facility, it should be possible to approach the positional accuracies and precision that are available in hot cells, and it should be possible to have small collimator apertures and do diametral scanning of fuel rods as currently performed in hot cells. Currently, one of the fuel vendors is updating its poolside capability to include computer-controlled data collection and onsite data analysis via computer. With a positional accuracy of 0.127 mm (0.005 in.) and an angular resolution of 5^{o}, the new system will significantly improve the company's gamma scan capability and will approach the capabilities of hot cell facilities.

Proper design of poolside facilities would permit accurate burnup measurements and reconstruction of radial isotopic distribution. This would avoid the expense of hot cell examinations. The following section on hot cell gamma scanning provides an overview of the types of gamma scanning capability that exist for irradiated fuels.

6.2.9 Hot Cell Gamma Scanning

Scanning of fuel rods in a hot cell provides a carefully controlled environment suitable for performing precision gamma scanning. One fuel vendor indicated that normally all their gamma scan measurements are done at a hot cell and that they considered this a problem separate from poolside inspection. Another fuel vendor has hot cell capabilities, including a gamma scanner. Their hot cell gamma scanner has a drive accuracy of 0.762 mm (0.03 in.) and a precision of approximately 0.254 mm (0.01 in.). The collimator on the in-cell unit is smaller, and discrete points are measured for burnup analysis. At the hot cell, they do continuous scanning with a sodium-iodide detector and sample specific points with a Ge(Li) detector. The in-cell measurements are made on specific fuel rods taken from a bundle and are used to measure burnup.

Table 6.4 shows some hot cell scanning parameters for contrast with poolside capabilities (Refs. 48-62). Although improved positioning accuracy and smaller collimator slits (higher resolution) are evident with gamma scanning systems in hot cells, the associated long scanning times are not compatible with poolside inspection operations. Techniques such as quantitative gamma scanning (Refs. 43 and 56), three-dimensional reconstruction, and scans of sectioned fuel rods (Ref. 63) are performed at hot cell installations, but they are not presently feasible at poolside.

6.3 Summary and Conclusions

Gamma scanning is a technique used to nondestructively gain information on fuel performance, and its major use is in the assessment of new fuels. This is seen in both the historical development of LWR poolside inspections and in the current measurements at hot cell facilities. All the fuel vendors have gamma scan capability. At present, one fuel vendor is developing an advanced gamma scanner. All the fuel vendors have performed poolside gamma scanning during the first few years of their commercial activities. Since that time, one fuel vendor has dropped their poolside capability for such testing; however, they presently have an EPRI-sponsored poolside program to gamma scan fuel rods for power distribution. Currently, most of the other vendors seldom gamma scan during poolside inspections. Thus, gamma scanning is not a routine poolside testing technique, and discussions with the fuel vendors indicate that, in general, the frequency of gamma scanning is less than once per year. Most of the fuel vendors have access to hot cell gamma scanning capabilities, and this seems to meet their present requirements. It is estimated that over 90% of the hot cell inspections by gamma scanning are involved with developmental fast reactor fuels.

Poolside gamma scanning is used primarily to measure active fuel column height and axial gaps in the fuel column. Fuel column height measurements can be made to $\pm$0.660 mm ($\pm$0.026 in.), and gaps in the fuel column as small as $\pm$0.152 mm ($\pm$0.006 in.) can be resolved. These numbers represent the best reported results and typical results would be four to ten times worse (see Table 6.3). Power distributions are also measured at poolside by a few of the fuel vendors.

TABLE 6.4. Laboratory Gamma Scanner Capabilities

Facility	Positional Accuracy or Precision, mm (in.)	Detector[a]	Collimator, mm (in.)	Data[b] Acquistion	Approximate[c] Scan Times, min/mm (min/in.)
Lab 1	0.0381 (±0.0015)	Ge(Li) 7.1 cc	--	MCA, MCS	0.12 (3)
Lab 1	--	Ge(Li) 30 cc	--	--	--
Lab 2	0.0254 (0.001)	Ge(Li) 25 cc + NaI A.C.	0.102x12.7 (0.004x0.5) 0.79 (0.031) dia	MCA	39.4 (1000)
Lab 2	±0.0508 (±0.002) Axial, ±0.0127 (±0.0005) Diametral	Ge(Li) + NaI A.C.	0.102x12.7 (0.004x0.5) 0.254x12.7 (0.010x0.5) 0.508x12.7 (0.020x0.5)	MCA + PDP 8	
Lab 3	--	Ge(Li) 3 cc	0.508x20.1 (0.020x0.79) 1.02x20.1 (0.404x0.79) 2.03x20.1 (0.080x0.79)	RM, MCA	0.002-3.94 (0.06-100)
Lab 4	--	Ge(Li) 22 cc	0-6.10x25.4 (0-0.24x1.0) Variable	PDP/11-20	0.79 (20 min) Spectrum
Lab 5	±0.508/305 (±0.002/12) Axial	Ge(Li)	0-1.27x12.7 (0-0.05x0.5)	CAMAC + Computer	7.87 (200)
Lab 6	Hand operated	NaI	0.127-12.7x178 (0.005-0.02x7) Variable	MCA	
Lab 7	0.00102 (0.00004) (?)	NaI Ge(Li)	1.02x15.7 (0.04x0.62)	RM, MCA	0.33, 42.5 (8.5, 1080)
Lab 8	±2.03 (±0.08)	NaI	0.508x? (0.02x?)	RM	--
Lab 9	±0.127 (±0.005)	Ge(Li) 8 cc	0.254x12.7 (0.010x0.5) 1.02x12.7 (0.040x0.5)	MCA, MCS	0.87 (22)
Lab 10	±0.787 (±0.031)	NaI Ge(Li) 9 cc	6.35 (0.25) dia	RM, MCA	0.04 (1)
Lab 11	±0.0254 (±0.001)	NaI	0.508x12.7 (0.02x0.5)	RM, MCA	0.002 (0.05)
Lab 12	--	Ge(Li)	0.254x17.8 (0.01x0.7) 0.254x22.3 (0.01x0.9) 1.27x6.35 (0.05x0.25)	Scalars, MCA, RM	0.001 (0.03)

(a) NaI A.C. indicates a Compton suppression detector around the primary detector.
(b) MCA = multichannel analyzer, MCS = multichannel scaler, RM = Ratemeter + Recorder.
(c) Scan times vary with procedure and listed times respresent times for published procedures.

In this case an accuracy of 3% is claimed by one fuel vendor for measurements of the ^{140}La used in power distribution determinations.

Poolside gamma scanning takes on the order of one hour per full-length scan, in addition to the time needed to set up the equipment and to handle fuel. Setting up the equipment can take several days, and 24 hours was the minimum time mentioned. The gamma scanning apparatus requires about 2.32 m^2 (25 ft^2) of deck space and a comparable area in the pool. It is difficult to provide an accurate number due to the diversity in the facilities available.

Gamma scanning at poolside is less sophisticated than hot cell scanning. At poolside, for example, diametral scans across the fuel rod cross section are never performed, and the position accuracy is generally greater than $\pm$1.27 mm ($\pm$0.050 in.). By comparison, the position accuracy in a hot cell is typically $\pm$0.0508 mm ($\pm$0.002 in.). On the other hand, scanning of a single rod in a hot cell can take several days, while poolside scanning of a single rod takes about one hour. The quantity of information obtained at the hot cell is much greater than at poolside. In the hot cell, specific isotopes are investigated (for example, ^{137}Cs is volatile under the conditions reached in a fast breeder reactor fuel rod and concentrates in specific regions). The redistribution of specific isotopes across the diameter of a fuel rod is also investigated in the hot cell. This contrasts with poolside inspections where one generally looks for gross activity changes or at specific isotopes with low resolution detectors.

Poolside capability could be upgraded to nearly equal hot cell facilities for accuracy and resolution. An intriguing possibility is the use of poolside facilities to resolve diametral distributions of isotopes, thus avoiding costly hot cell destructive examinations. Any improvement in poolside capabilities would probably result in a larger installation requiring more time to set up and more time per scan.

Counting standards are not generally used at poolside. Development of a resolution/accuracy standard could be useful when comparing results among fuel vendors, but it is not required by individual vendors. Standards are difficult to fabricate and are presently in use at only one laboratory (Ref. 43).

7. SIPPING

7.1 Introductory Comments

Fission-product activity in the reactor coolant at higher than normal background levels[a] is an indication that perforation of fuel rod cladding has occurred (Ref. 64). Sipping is an inspection technique used to identify the irradiated fuel bundles that contain the leaking fuel rods. Evaluation of fuel by sipping is used when it is practically certain that the reactor core contains failed fuel (i.e., the reactor coolant activity is judged to be excessive) (Ref. 18). With commercial reactor fuel, sipping is normally performed onsite during scheduled refueling outages.

During reactor operation, gaseous and soluble fission products accumulate inside the individual fuel rods of a fuel bundle. These radionuclides are released into the primary coolant of the reactor if the fuel rod integrity is lost. Traditionally, plant off-gas trends yield the first indication of a potential fuel problem that may require corrective action or additional evaluation. Overall fuel performance patterns in commercial BWRs have been anticipated by means of plant off-gas trends and monitored by studying fuel sipping results (Ref. 12).

A fuel bundle with perforations in the fuel rod cladding is commonly referred to as a "leaker bundle," "leaker assembly," or simply as a "leaker." Sipping permits a plant operator to check the mechanical integrity of irradiated fuel bundles that are to be returned to the reactor and of spent fuel bundles when they are to be transferred to a spent fuel storage site or to a reprocessing plant.[b] By using this inspection technique, leakers can be removed from core loadings to reduce noble gas and iodine release to the environment and to decrease in-plant radiation levels due to fission products. Leakers among discharged spent fuel can be detected by sipping off the "critical path,"

(a) Uranium present in core components or uranium impurities previously deposited on reactor internals produce the background radiation (Ref. 64).

(b) In the United States, the apparatus for sipping fuel can remain at the plant or be transported from one site to another. In Europe, the apparatus typically remains permanently in the spent fuel pool (Ref. 18).

thereby reducing contamination problems during the transfer of those fuel bundles to a spent fuel storage site or to a reprocessing plant.

Nonrecoil off-gas activity comes from fuel rods that contain fission product inventories and have small perforations in fuel rod cladding. Off-gas activity with a recoil distribution is indicative of the fissioning of uranium surface contamination (tramp uranium) that is on fuel rods or is in or plated on nonfuel reactor internals or the fissioning of fuel pellets that, because of large defects in the cladding, are in direct contact with the coolant (Refs. 8, 9, and 19). In contrast to nonrecoil off gas, recoil off gas is not significantly eliminated by sipping because neither small cladding perforations nor fission product inventories are involved. Thus, the reduction in the amount of nonrecoil off gas is a "true measure of the reliability of defective-fuel detection methods" (i.e., a measure of sipping effectiveness) (Refs. 19 and 64). Hence, sipping produces a quantitative measure of fuel performance, especially for comparing performance among designs (Ref. 12). Sipping as a means of detecting leaker bundles is not an exact diagnostic technique (see 7.4.3): Sipping preferentially identifies fuel cladding breaches that happened late in the reactor cycle (Ref. 13).

One European paper (Ref. 65) indicates that although many LWRs use at least one of the sipping techniques, little detailed knowledge has been assembled on the release rates of fission products after reactor shutdown. That paper presents data on the long-term (to seven months) release of activity to a spent fuel storage pool.

7.1.1 Measurement Principles

Breached fuel cladding releases fission product activity even when the reactor is shut down and the temperature is as low as 293K (20°C) (Ref. 65). The principle of sipping is based on determining the presence and magnitude of escaping fission products from leaking fuel rods in irradiated fuel bundles that are in the sipping apparatus. In-core and out-of-core sipping are commonly used. Both techniques use radiochemical methods to detect excessive fission product activity, which can be an indication of fuel cladding perforation(s) (Ref. 12).

To successfully detect failed fuel by sipping, material must be expelled producing the radiochemical (or other) signal from the fuel rod(s). A breach in the fuel rod cladding may only allow a small release of radionuclides into the coolant in the sipping apparatus, and meaningful data cannot be obtained unless substantial buildups of these radionuclides are present (Ref. 66). Release of fission product activity can be accelerated several ways: (a) increasing the temperature (and, hence gas expansion), (b) reducing the pressure (i.e., drawing a partial vacuum) (Ref. 19 and 67), or (c) increasing the speed of the fluid past the cladding breach (Ref. 18). Subjecting a fuel bundle containing one or more failed fuel rods to a temperature rise has two effects: (1) the volume of fission gases within the fuel rods expands and increases the release of volatile fission products from rods with cladding perforations and (2) the release of water-soluble fission products to the water in the sipping apparatus is increased. Comparisons of activity measurements of the environment surrounding the fuel bundle before and after heating ("soaking") show that leaker detection can be improved with extended heating time. Several factors limit the setting of the heating time: the maximum allowable cladding temperature and a desire to keep the time used for poolside operations low while still obtaining meaningful sipping signals.

By circulating gas (e.g., nitrogen) or water past the cladding perforation, the gamma activity released by breached fuel rods (Ref. 18) can be better measured. Indications of failed fuel can be obtained by gamma counting selected fission products entrained in the circulated gas or by measuring the gamma activity of fission products (element by element) entrained in the circulated water.

A "stripping" process has been mentioned as a means for measuring noble gas release after reactor shutdown with the fuel bundles submerged in water (Ref. 65).

7.1.2 Types of Sipping in General Use

7.1.3.1 Wet Sipping

In general, the wet sipping technique involves testing a fuel bundle under water in the spent fuel pool (i.e., out-of-core sipping) or reactor core (i.e., in-core sipping) and identifying those bundles that leak by detecting the

release of leachable fission products (primarily iodine and cesium) to an isolated volume of coolant. One advantage of wet sipping is the inherent safety of the technique: the fuel bundle is always submerged in water. The sensitivity of wet sipping is less than that for dry sipping (see following section). In contrast to dry or vacuum sipping, wet sipping has a rapid signal loss (one- to two-day decay half-life), which means sipping should be completed within a few weeks after reactor shutdown (Ref. 64).

The sensitivity and reliability of wet sipping is measurably increased with 100% isolation, making this situation most desirable (Ref. 64). Out-of-core wet sipping is employed at most LWRs. It is done by removing a fuel bundle from the core and isolating it in a sealed can in the spent fuel storage pool. An example of out-of-core wet sipping equipment for BWR fuel is shown in Figure 7.1. The individual fuel bundles are moved into the isolated environment

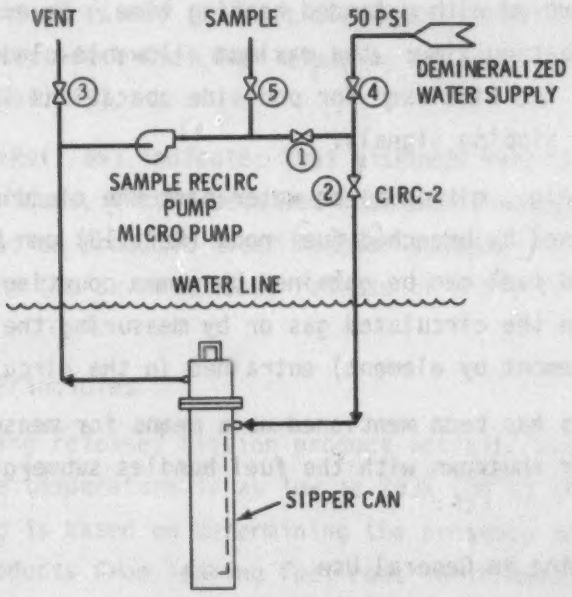

FIGURE 7.1. Example of Schematic Diagram of the Piping for Out-of-Core Wet Sipping of BWR Fuel Bundles

(enclosed sipping can). Figure 7.2 (Ref. 66) is also an example of the equipment used for wet sipping or combination wet/dry (hybrid) sipping of BWR fuel. Similar equipment is used with PWR fuel.

In most cases of out-of-core wet sipping, after the fuel bundle is loaded into the can and the can lid is sealed, the contaminated water (i.e., spent fuel pool water) inside the can is replaced with clean, demineralized water to reduce the background. The pool water is expelled from the can interior by using 1) compressed dry air or nitrogen, after which the can is filled with demineralized water, or 2) forced circulation flushing with demineralized water. The contained water is allowed to heat up ("soak") for a predetermined extended time period. In some cases, the contained water is recirculatred (mechanically mixed) during the soak period to build up the inventory of fission products, which results in an increase in leak detection sensitivity. At the end of the soak period, the representative water sample is taken. In other cases, the contained water is not mechanically mixed during the soak period but is pumped for a short time ($\sim$3 min) through the fuel bundle before the representative water sample is taken. Water samples are typically radiochemically analyzed to determine the presence and magnitude of specific fission products.

Out-of-core wet sipping has one disadvantage: the crud layers on the fuel bundles may contain significant quantities of the nuclide of interest (Ref. 64) but the concentrations of that nuclide can vary substantially. This can cause considerable scatter in the background concentrations for sound fuel bundles, resulting in reexamination of a significant fraction of those fuel bundles whose integrity was questioned initially.

There is a primary advantage to wet sipping at a BWR: sometimes it can be done without removing the fuel bundles from the core. In-core wet sipping is, in fact, not possible at PWRs (Ref. 64).

In-core wet sipping is typically associated with BWRs, and multiple fuel bundles (with channels in place) are sipped simultaneously. This is done by placing a sampler (also known as a sipper head or hood) over the fuel bundles to be tested.

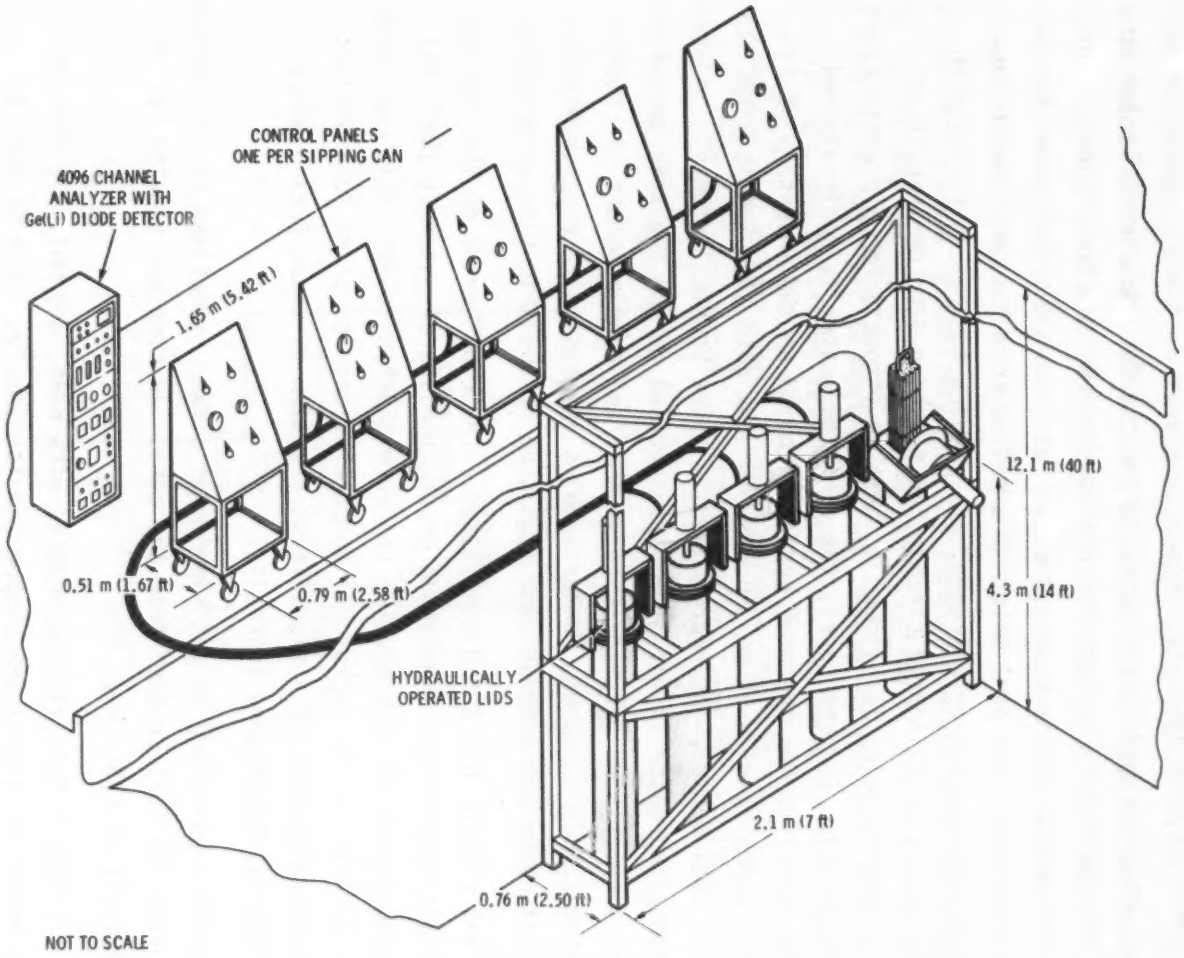

FIGURE 7.2. Example of System for Out-of-Core Wet Sipping or Combination Wet/Dry (Hybrid) Sipping of BWR Fuel (Ref. 66). (Similar equipment is used with PWR fuel; however, there are slight differences between the PWR and BWR systems. Reprinted with permission from Nuclear Assurance Corporation.)

Typical in-core wet sipping equipment used for domestic BWR fuel is shown in Figure 7.3. The sampler tests four bundles (i.e., a control rod cell) in situ; fuel bundles are not moved, and the channels are not removed from the fuel bundles. The fuel channel and sampler isolate the individual fuel bundles. At some foreign BWRs, up to eight fuel bundles are wet sipped simultaneously (Ref. 18).

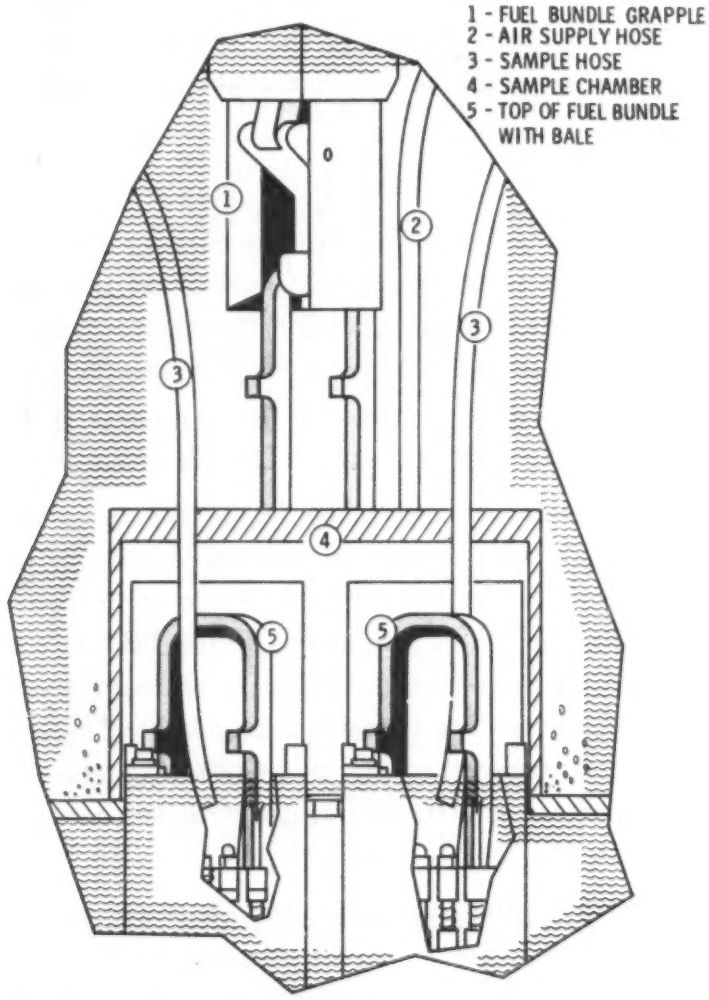

FIGURE 7.3. Cross Section of a Typical Sampler Used for In-Core Wet Sipping of BWR Fuel

In the case of in-core wet sipping, after the sample is in place, the soak period is initiated by interrupting the natural circulation of reactor primary coolant surrounding each of the fuel bundles to be sipped. Compressed air is used to stagnate the water and to lower its level in the sampler to the top of the fuel bundles. Water samples (e.g., from each of the four channels) are taken at the end of the soak period and radiochemically analyzed.

Reference 64 notes two disadvantages with in-core sipping at BWRs: (1) the concentration of fission products is reduced because of convection currents (a result of having the fuel channel open at the bottom end) and (2) sometimes there are high background radiation levels in the coolant surrounding sound fuel bundles.

7.1.3.2 Dry Sipping

The technique of dry sipping typically involves placing a fuel bundle in a can that is located underwater in the spent fuel pool or in the reactor vessel. Examples of out-of-core dry sipping equipment for BWR fuel are shown in Figure 7.4 and 7.5. An example of combination dry/wet sipping equipment for BWR fuel is shown in Figure 7.2. Some PWRs have in-core dry sipping equipment, which consists of one sipping can as part of the fuel handling machine.

The can is usually not sealed at the bottom (i.e., the can is bottomless or has holes at the base so it is always open to the spent fuel pool water). A lid is positioned on the top of the can and air or nitrogen is introduced into the top of the can to expel the spent fuel pool water inside the can down to a level below the lower end of the fuel bundle. After an appropriate soaking period during which the fission gases are released from cladding defects because of the increase in fuel rod temperature due to decay heat, water is allowed to re-enter the can and the air or nitrogen vented from the can is analyzed for noble gases.

Reference 64 notes the following advantages and disadvantages of dry sipping. The signals from dry sipping indicating the presence of fission products are very high, hence very sensitive. The signal also lasts for months or years after reactor shutdown. An advantage of dry sipping over wet sipping is that the signal is several orders of magnitude greater. The sensitivity of dry

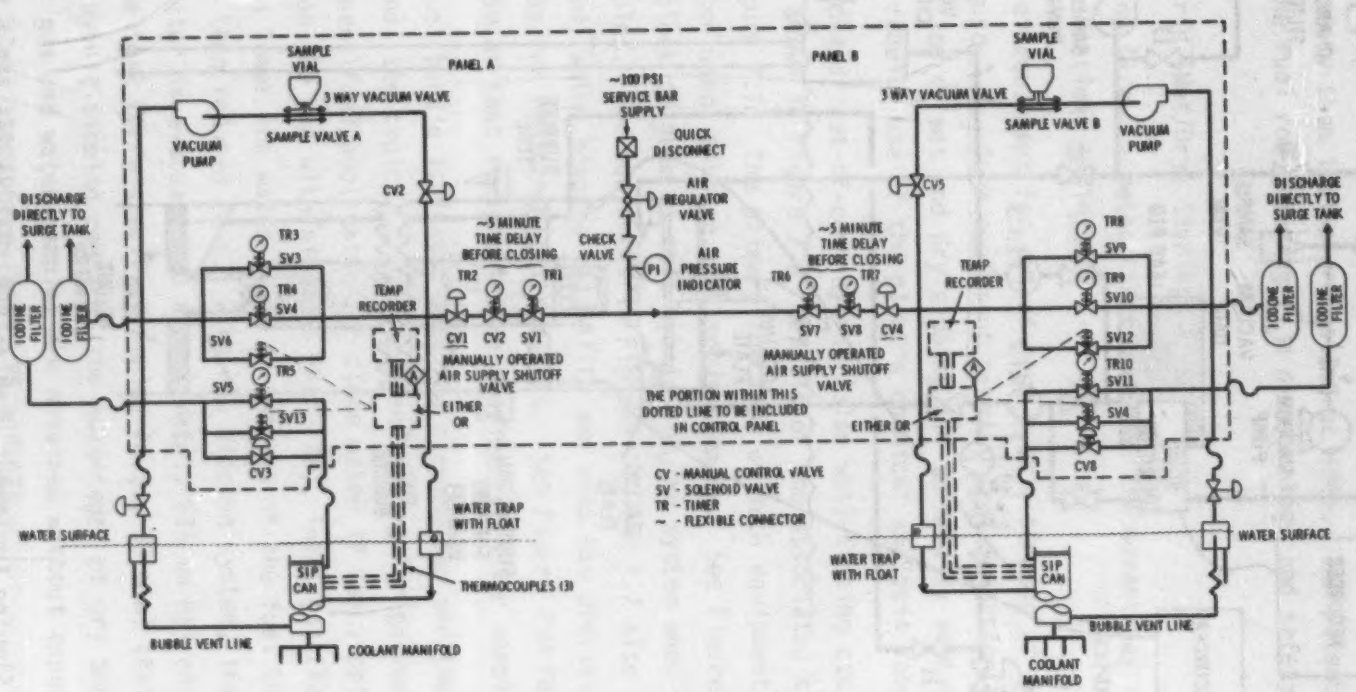

FIGURE 7.4. Equipment Used at One BWR for Out-of-Core Dry Sipping of Fuel (Ref. 17)

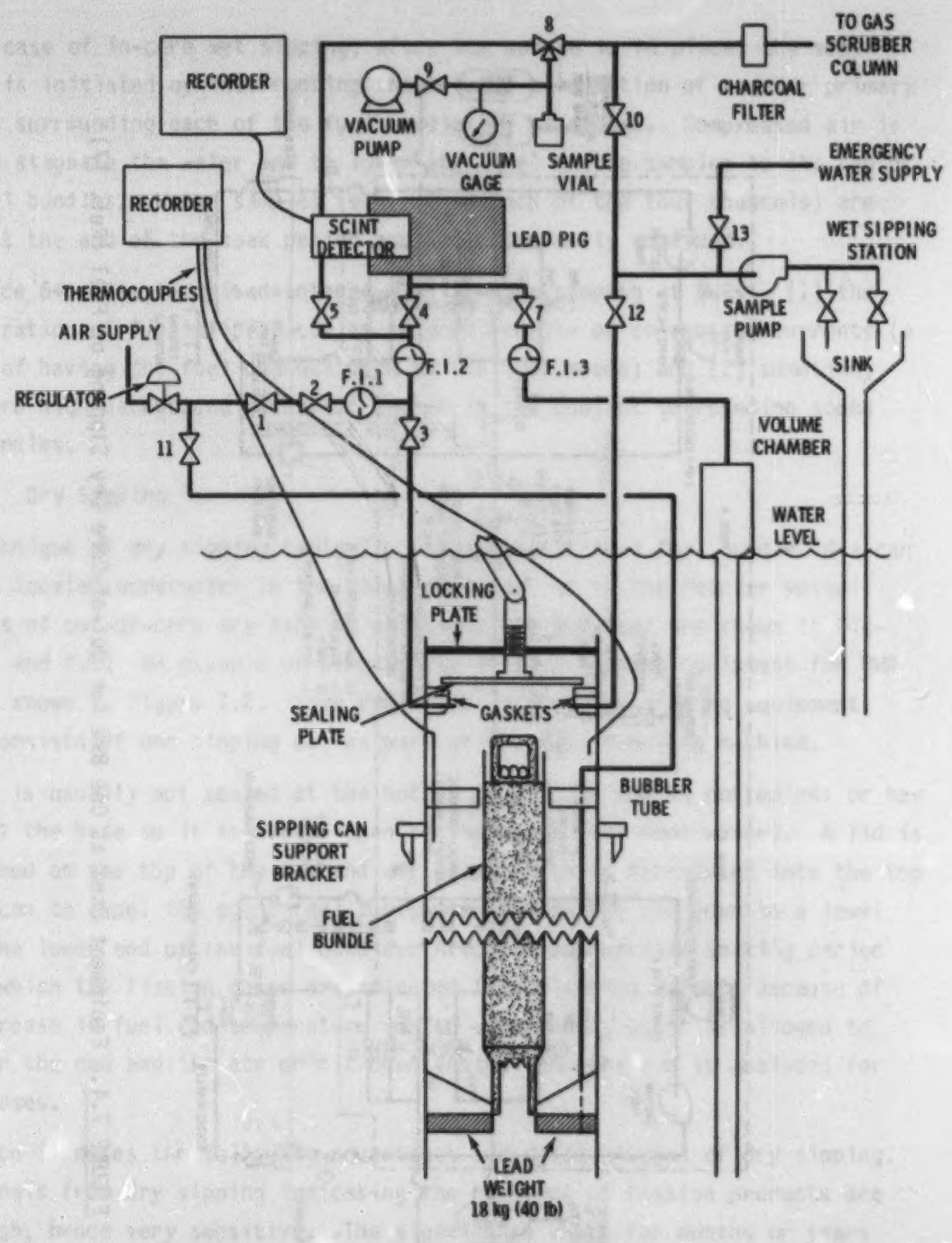

FIGURE 7.5. Dry Sipping Equipment Used on BWR Fuel in the Spent Fuel Storage Pool and in the Reactor Vessel at One BWR (Ref. 8). (The equipment was actually designed with a combination wet or dry sipping can and the associated sample stations.)

sipping is better than that of wet sipping because fission gas atoms migrate much more readily than iodine or cesium nuclides. The potential for overheating of the fuel rod cladding is a disadvantage and safety concern with dry sipping.

7.1.3.3 Hybrid (Wet/Dry) Sipping

Hybrid sipping (i.e., a method that combines the advantages of wet and dry sipping) is sometimes employed.

One example of equipment for out-of-core hybrid sipping of BWR and PWR fuel is shown in Figure 7.2. Such equipment permits leak detection by wet sipping or by a combination of wet and dry sipping and is totally self-sufficient (i.e., it does not require use of the plant's chemical analysis laboratory).

Another example of out-of-core hybrid (also wet) sipping equipment for BWR and PWR fuel is shown in Figure 7.6 Details of the associated sipping can are shown in Figure 7.7. The primary function of such equipment is the in-line (beta detector used) sipping of gaseous samples. See Figure 7.8 for a functional block diagram of that hybrid sipping system when sipping for gaseous samples. The equipment in Figures 7.6 and 7.7 also has in-line (gamma detector used) water sipping capability and also has provisions for removing water samples for radiochemical analysis. See Figure 7.9 for a functional block diagram of that equipment when sipping for water samples.

After the fuel bundle is loaded into the sipping can and the lid at top of the can is sealed, the typical procedure when sipping for gaseous samples is to force the spent fuel pool water (or clean water if the sipping can was flushed) from the can with nitrogen (Ref. 25), inert gas (Ref. 66), or air (Ref. 67) to lower the water level to the top of the fuel bundle. The gas pressure is then reduced (e.g., with one sipping system, the volume that is devoid of water is evacuated to approximately 635 mm Hg) and the system is permitted to soak for a specified period (e.g., 30 min) (Refs. 25, 66, and 67). Such hybrid sipping combines the advantages of dry and wet sipping in that gas or gas and water samples are obtained without exposing the fuel assembly to a gas atmosphere (Refs. 25 and 67).

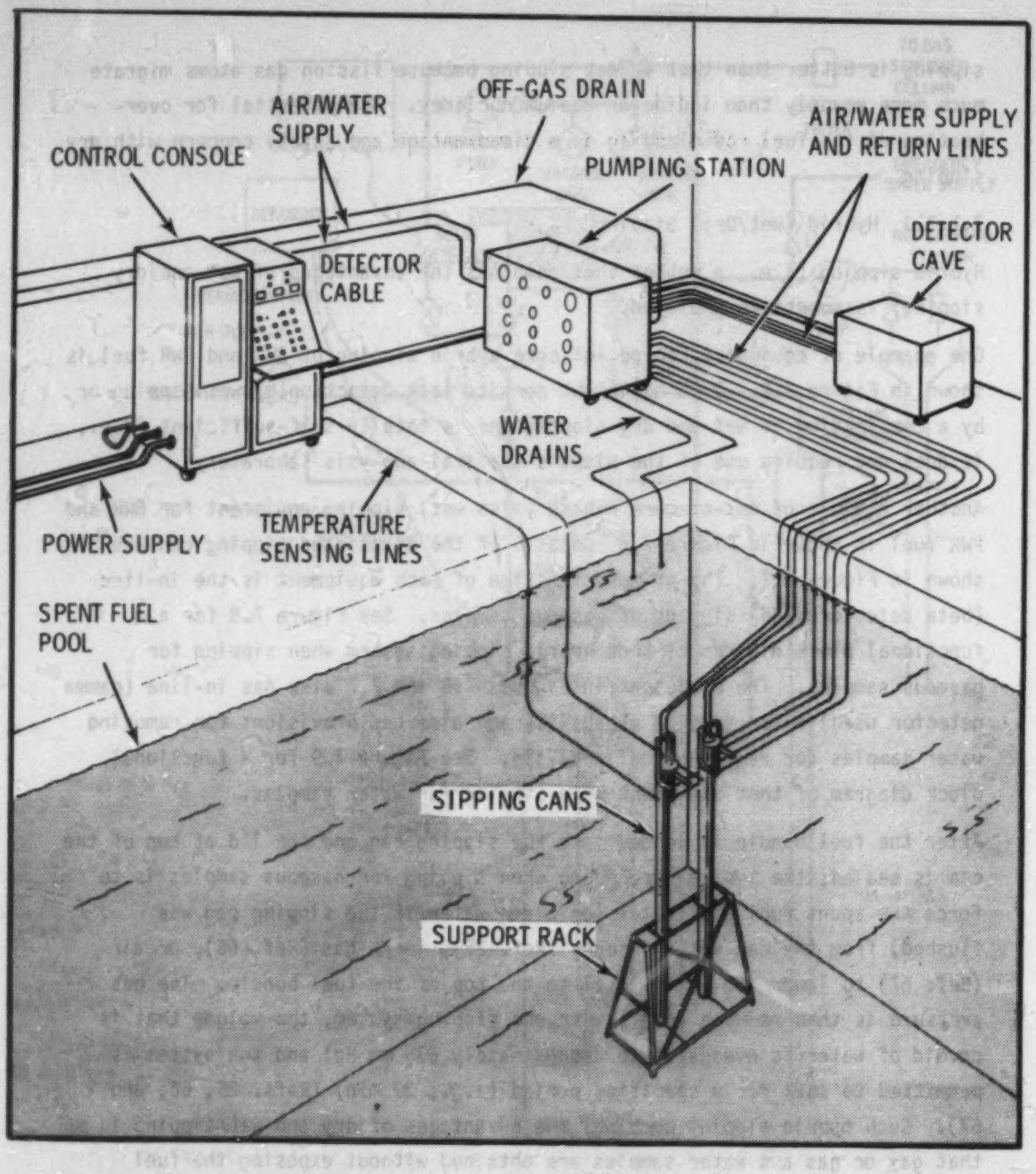

FIGURE 7.6. Example of Equipment for Out-of-Core Hybrid (also wet) Sipping of BWR and PWR Fuel (Ref. 67). (Reprinted with permission from Lake Shore, Inc.)

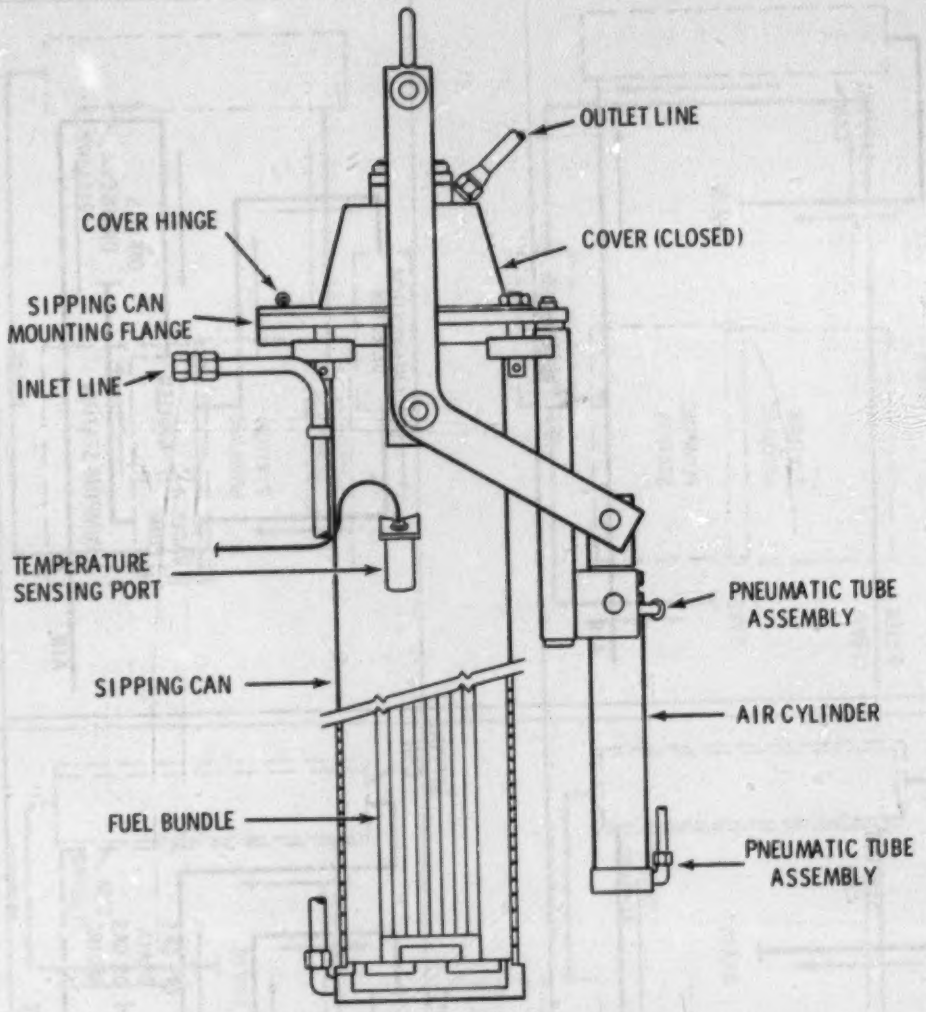

FIGURE 7.7. Details of Sipping Can from Figure 7.6 (Ref. 67). (Reprinted with permission from Lake Shore, Inc.)

7.1.3.4 Vacuum Sipping

A new sipping technique, vacuum sipping (also known as pressure sipping or pressure differential gas sipping) was developed to optimize the detection of gaseous radionuclides escaping from cladding perforations (Refs. 12, 19, 64, and 69). Release of fission gas (and other fission products) from defective fuel rods in a fuel bundle is accelerated in this method. Leaky fuel is identified via an on-line gaseous monitoring technique that also permits the fuel bundle to remain immersed in water during the entire sipping process.

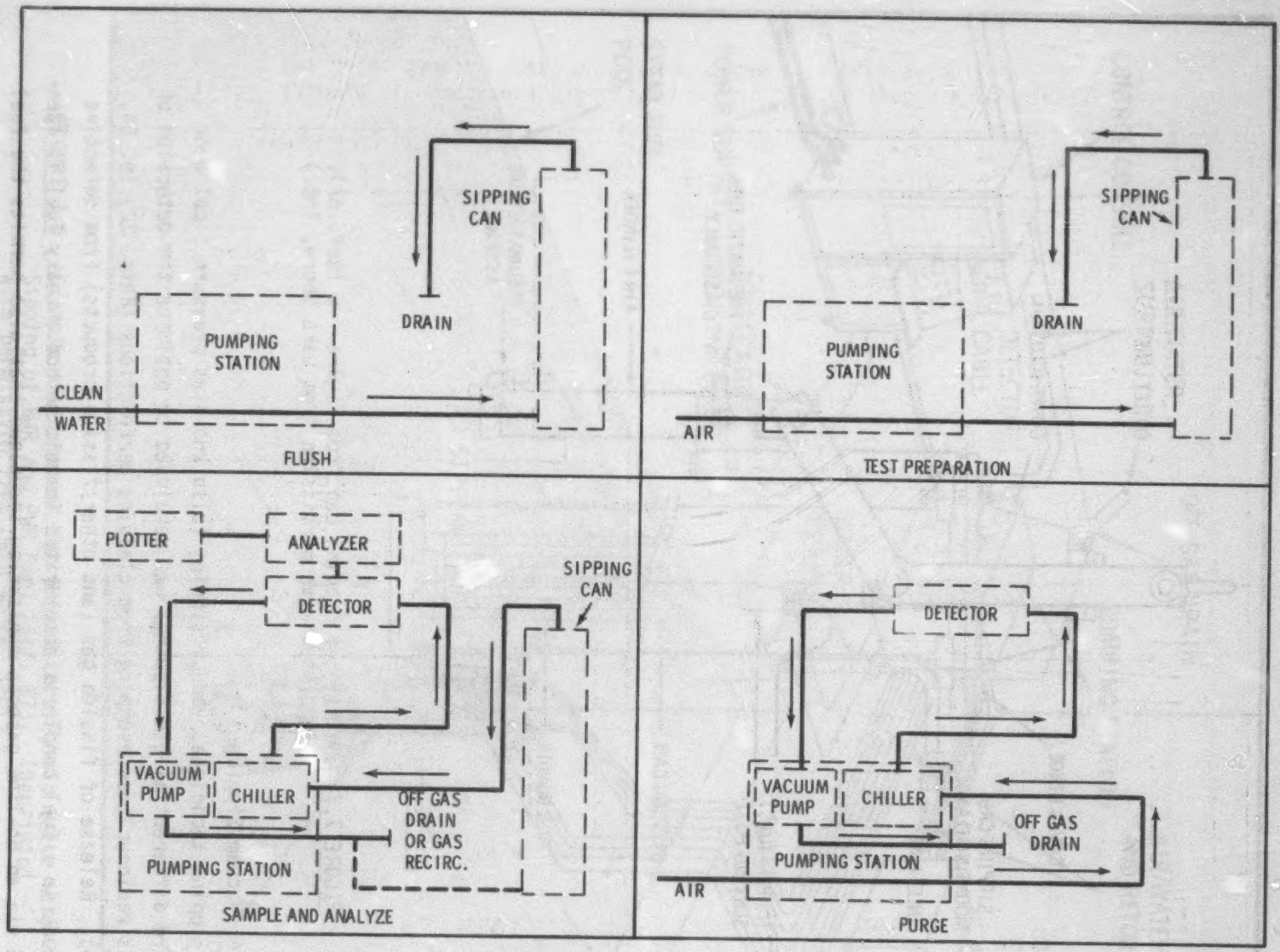

FIGURE 7.8. Example of Functional Block Diagram for a Hybrid Sipping System When Sipping for Gaseous Samples (Ref. 67). (Reprinted with permission from Lake Shore, Inc.)

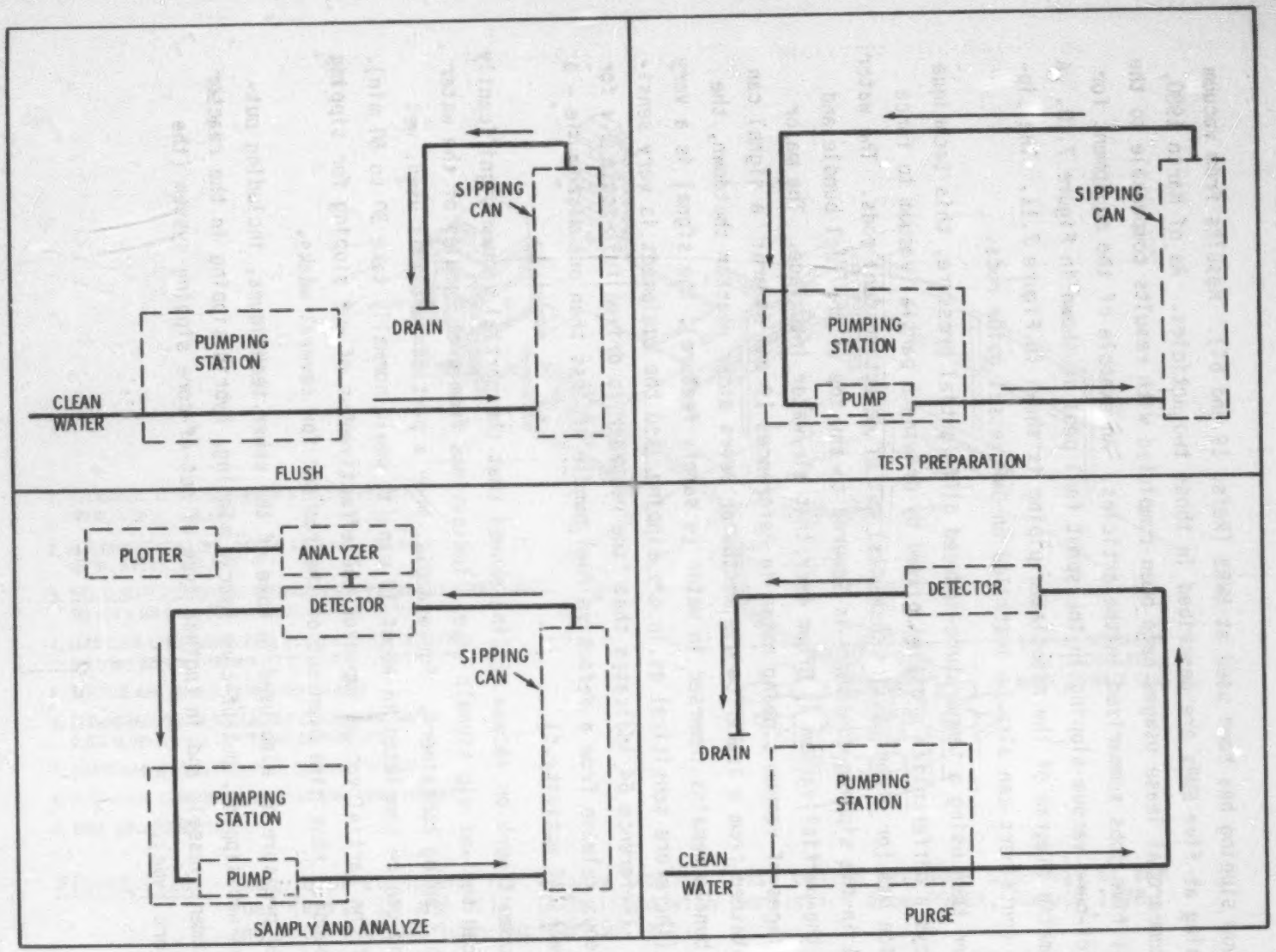

FIGURE 7.9. Example of Functional Block Diagram for Sipping System When Sipping for Water Samples (Ref. 67). (Reprinted with permission from Lake Shore, Inc.)

Vacuum sipping has been used at BWRs (Refs. 19 and 64). Results from vacuum sipping at five BWRs are described in those two articles. As of March 1980, 17 commercial lease usages have been completed with results comparable to the first five jobs summarized in the articles. An example of the equipment for out-of-core vacuum sipping in the spent fuel pool is shown in Figure 7.10. A schematic diagram of the associated piping is shown in Figure 7.11. The sipping containers can also be installed on BWR vessel guide rods.

Rather than using a temperature-induced differential pressure, this technique employs a differential pressure caused by drawing a partial vacuum to force fission gas (or other fission products) out of defective fuel rods. The water level in the sipping container is lowered to the top of the fuel bundle and then the partial vacuum is drawn over that air/water interface. The major advantages of vacuum sipping noted in References 19 and 64 are: a signal can be obtained from a leaker bundle months or years after reactor shutdown, the fuel bundle remains immersed in water (a safety feature), the signal is a very high (therefore sensitive) as in dry sipping, and the equipment is very sensitive. (Reference 64 indicates that "the recorder is driven full-scale ... for a gaseous release from a defective fuel bundle of less than one microcurie - a low level of activity.")

Development work on vacuum sipping showed that the partial vacuum significantly enhanced the wet sip signals (i.e., indications from grab samples of the water in the sipping container). For example, when a partial vacuum is used, wet sipping can be completed in about 10 min (it would normally take 30 to 60 min). Use of the partial vacuum improved the effectiveness of wet sipping for sipping fuel bundles that have been out of the reactor for several weeks.

Reduced pressure is also used in some of the other techniques, including out-of-core wet sipping, out-of-core hybrid sipping, hybrid sipping in the reactor containment vessel, and in another type of out-of-core sipping system (the fast-sort type).

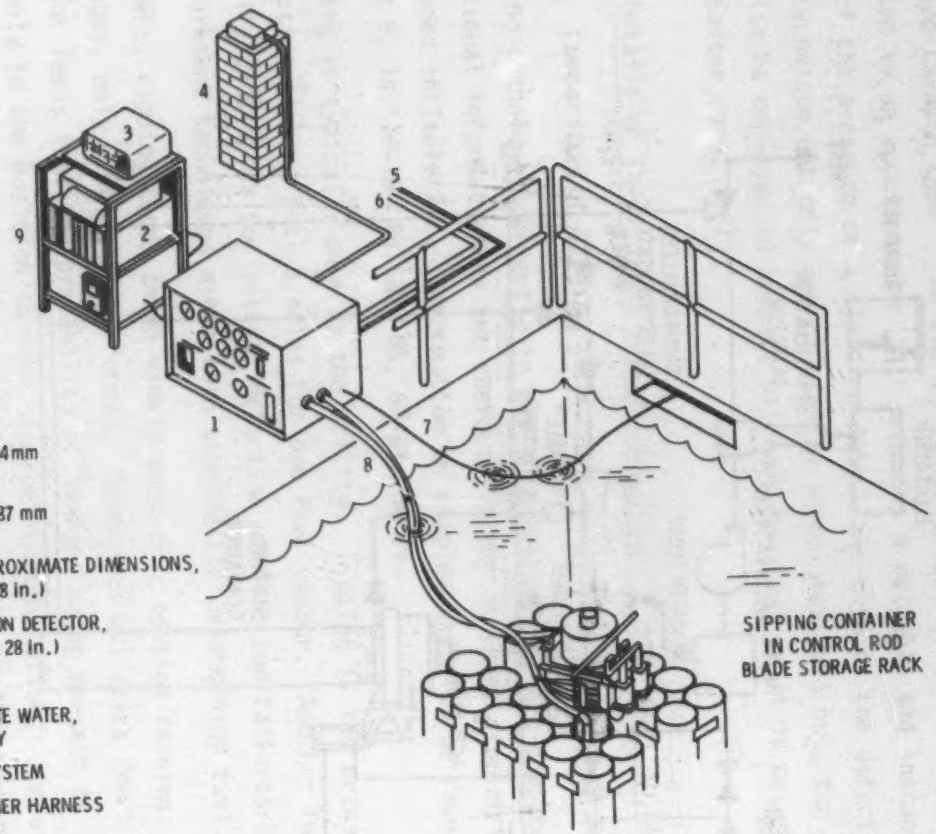
1. HYDRAULIC CONSOLE, 508 mm x 914 mm x 914 mm (20 in. x 36 in. x 36 in.)
2. ELECTRONIC CONSOLE, 533 mm x 533 mm x 787 mm (21 in. x 21 in. x 31 in.)
3. SOLID STATE ELECTRONIC CONTROLLER APPROXIMATE DIMENSIONS, 381 mm x 305 mm x 205 mm (15 in. x 12 in. x 8 in.)
4. LEAD CAVE CONTAINING BETA SCINTILLATION DETECTOR, 305 mm x 305 mm x 711 mm (12 in. x 12 in. x 28 in.)
5. SERVICE AIR, 0.62-0.69 MPa (90-100 psig)
6. DEMINERALIZED OR RECLAIMED CONDENSATE WATER, 0.076-0.095 m3/min (20-25 gpm) CAPABILITY
7. DRAIN HARNESS TO FUEL POOL CLEANUP SYSTEM
8. HYDRAULIC CONSOLE TO SIPPING CONTAINER HARNESS
9. 110V, 60Hz POWER SUPPLY
SIPPING CONTAINER IN CONTROL ROD BLADE STORAGE RACK

FIGURE 7.10. Example of Equipment for Vacuum Sipping (also called pressure sipping) of BWR Fuel (Refs. 19 and 64). (Reprinted with permission from POWER, August 1978, and from the American Nuclear Society.)

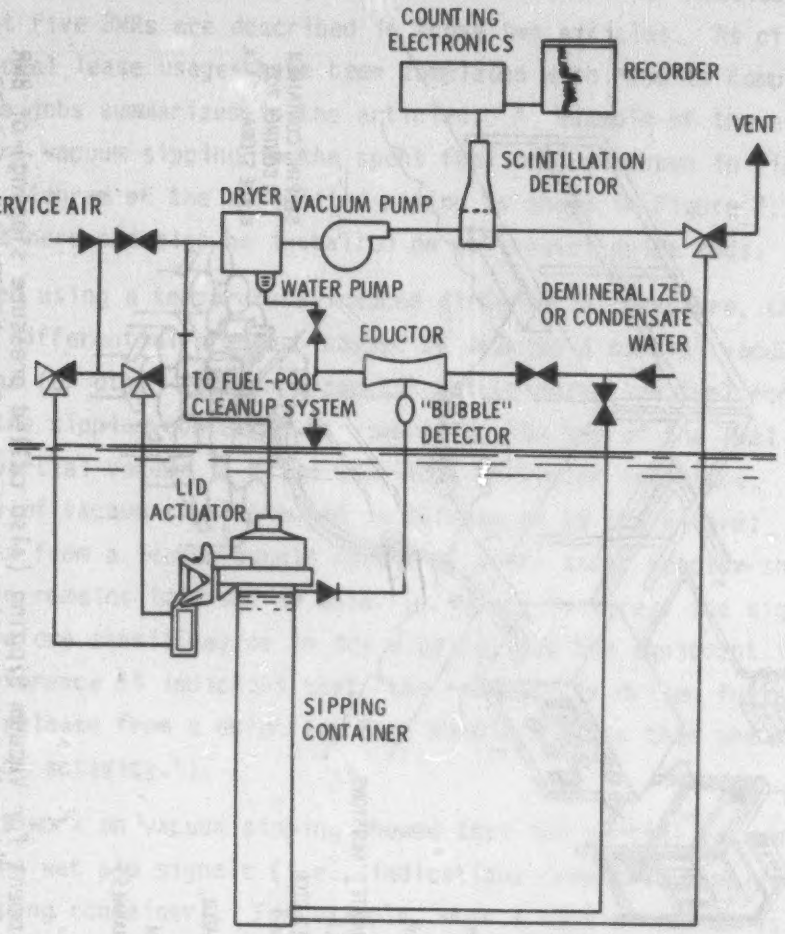

FIGURE 7.11. Example of Schematic Diagram of the Piping for Out-of-Core Vacuum Sipping of BWR Fuel (Ref. 64). (Reprinted with permission from POWER, August 1978.)

7.1.4 Other Types of Sipping

The fuel failure detection system installed at one domestic PWR employs a different sipping method (a rapid-sort type) (Ref. 70). The technique is used with in-core and out-of-core failed fuel detection systems. This technique uses a change in the relative fluid pressures so that the fluid within the fuel rods is at a higher pressure than the water in which the fuel bundle is immersed. If there are perforations in the cladding of any of the fuel rods,

a bubble (or bubbles) of fluid or other material from inside the fuel rod is expelled through them. The vibrations associated with these emissions are detected by an accelerometer that produces a reliable and instantaneous indication of the presence of a cladding defect and also of the defect location. This technique not only can be used on irradiated fuel but, for the first time, can also be employed to inspect unirradiated fuel as it is being installed in the reactor core.

7.2 Details on In-Core and Out-of-Core Sipping Techniques in Current Use

7.2.1 Comparison of Sipping Techniques and Use of Sipping at BWRs and PWRs

Sipping techniques currently in use at domestic LWRs are compared in Table 7.1. Additional information on the characteristics of those sipping techniques is included in Table 7.2. Information on sipping may also be found in References 8, 14, 16-19, 25, 30, 66, 69-84, 86-91.

Sipping is typically done by the utility. Sipping is the primary means of detecting leaking fuel bundles for one fuel vendor. Another fuel vendor relies heavily on sipping for initial detection of fuel rod failures but relies on measurement techniques other than sipping for determining fuel performance.

At BWRs, sipping tends to be widely used in a routine fashion. In 90% of the outages, only sipping is performed. Sometimes utilities don't sip if the fuel vendor feels that the probability of leakers being present is low. The vendor is only in the position to make sipping recommendations; the utility makes the decisions and considers critical path constraints as very strong factors. In-core sipping has always been a critical path item for a BWR outage. Because of critical path constraints and if operating effluent radioactivity levels are low, even sipping may not be performed during an outage.

At PWRs, the tendency is for sipping to be used only if necessary, and some PWRs currently have no plans to conduct sipping. Sipping is not routinely conducted at certain PWRs because, based on coolant activity, several fuel vendors and utilities feel that there is no need to leak test the fuel bundles.

TABLE 7.1. Comparison of Sipping Techniques Offered or Employed by Fuel Vendors and Utilities That Were Visited by NRC and PNL

Company	Sipping Technique	Requirement	Typical Rate No. of Fuel Bundles/Day	Approximate Leaker Detection Efficiency
A	Company A offers a sipping system of its own design as NSSS option.(a)			
	Company A has purchased a two-can system(b) from Company I to provide portability; the intent is to offer sipping services to utilities with PWR fuel. This out-of-core system permits leak detection by both wet sipping and hybrid sipping.		(c)	90-95%
B	Company B offers in-core dry sipping system option to the utilities. This system involves one sipping can as part of the fuel handling machine.(d)			
	Company B has developed their own equipment for out-of-core wet sipping.(e) Three cans may be used. They could possibly add one more can but are limited by the fuel handling capability.		~27(f)	high(g)
C	Company C does no sipping themselves. When Company C's fuel is sipped, the utility does it.(h)			
D	The utility is responsible for sipping (and it owns the data) and for sipping equipment and procedures.(i) Company D offers sipping equipment, procedures, and services on a competitive commercial basis. The minimum capability for sipping at each BWR is one four-bundle heat for in-core sipping(j) and one can for out-of-core sipping. The sipping techniques (including time estimates(k)) described by Company D are:			
	In-core wet sipping (old design)(l)	1) >85% power prior to shutdown 2) Sipping starts 3-8 days after shutdown	120-190(m)	60-80%(n)
	In-core wet sipping (new design)(o)	1) Sipping starts within ~3 weeks after shutdown 2) There are few leakers	120-190 (with one head)(m) ~150-500 (with four heads)(m,p)	80-100%

(a) Several plants have one, but only the one at one PWR has been throughly checked out None have been used to actually leak test fuel.
(b) As of the date of the visit, Company A had not yet used this system.
(c) Company I indicates that a five-can system is faster than the two-can or three-can system for PWRs; using a five-can system, a sipping rate of 40-60 fuel bundles per 24-hour day is possible depending on reactor plant equipment operating restrictions.
(d) Some utilities have taken this option and have the in-core dry sipping capability.
(e) The spent fuel pool bridge crane is required for the movement of the fuel bundles. Current sipping time constraints are not due to sipping equipment but are due to fuel handling requirements. With Company B's sipping concept, it is possible that sipping could be done over a standard fuel rack position. New high density fuel storage racks may present some additional mechanical interface problems.
(f) In two publicly available reports, it appears that 229 PWR fuel bundles were sipped (217 sipped, 12 resipped) in 204 hours. Company B said foreign plants can sip faster than U.S. plants because they don't have to verify each fuel move.
(g) Company B's sipping is based on a foreign company's experience. That foreign company assumes an efficiency of over 99% for out-of-core wet sipping of PWR fuel and also indicates that the efficiency for in-core wet wipping of BWR fuel is less than that because of the lower heating in the BWR sipping test.
(h) Company C's fuel has been sipped at four BWRs and three PWRs. Company C's fuel at another PWR has not been sipped because the coolant acitivity has been extremely low. One BWR was the only site where Company C encountered crud release during sipping. That release of crud reduced visibility in the pool to ~0.5 m.

TABLE 7.1. (contd)

Company	Sipping Technique	Requirement 3) There are low concentrations of radioactive fission products	Typical Rate No. of Fuel Bundles/Day	Approximate Leaker Detection Efficiency	Comments
	Out-of-core wet sipping	None	40-60(l)	>95%	(i) All of Company D's fuel bundles are sipped after the poolside examinations are completed. Generally, every irradiated fuel bundle that is to go back into the core is sipped (hence, sipping could be on the critical path). (j) In-core sipping has always been (and still is) a critical path item for the reactor outage. Company D indicated that the most overseas utilities use in-core wet sipping methods. (k) The following estimates were given by Company D on the time to complete sipping of a full core of fuel bundles [this could presumably mean up to 764] by three techniques: in-core sipping, 8 days; out-of-core sipping, 3 to 4 weeks; and pressure differential sipping, 6 to 8 days. (l) Used in second and third generation type BWR plants. (m) Assumes a 24-hour work day. (n) The approximate leaker detection efficiency is sometimes better or worse than this. (o) In-core wet sipping by the newly designed technique has indicated the highest leaker detection efficiency and will be Company D's first choice when recommending a sipping technique. It also involves no moving of fuel bundles. (p) Can be used in sixth generation type BWR plants. (q) Company D has patented vacuum sipping, a method that yields the high (hence sensitive) signals produced by dry sipping but with the inherent safety of wet sipping (i.e., the fuel bundle remains covered with water). This technique is rapidly becoming the preferred sipping method at BWRs; it has been commercially applied at some domestic BWRs. The equipment is fully automated, which decreases manpower needs and personnel exposure and provides potential for significantly reducing the critical-path outage time needed for detection of leakers. Because an on-line detector is used in vacuum sipping, data analysis is simplified in comparison to that with wet sipping techniques.
	Out-of-core vacuum [pressure differential (gas)] sipping(q), with the sipping container located in a control rod blade storage rack; however, the equipment is also designed for use on the reactor vessel guide rods at BWRs.	None	~80-200	>95%	
	Out-of-core dry (gas) sipping(r)	None	20-50(l) ~14(t)*	--	
E	Company E is currently evaluating an updated version of a sipping system.(s) Company E reported in 1972 that its portable system for fuel evaluation was normally used away from the reactor containment vessel [i.e., the out-of-core sipping was done in the spent fuel pool]; however, the leakdetection portion of the system could be installed in the vessel if necessary. The leak detection equipment associated with the portable system is capable of using three techniques: wet sipping, dry sipping, and hybrid sipping. Hybrid (combination wet/dry) method is normally used.				
F	Company F started with in-core sipping and then went to out-of-core wet sipping at one site with BWRs. Company F has not done in-core sipping since about 1973.(u) Company F has their own sipping equipment, which consists of a six-station system made by Company J. The system is manually operated through a control console (fluid actuators).(x) Company F is working with Company J to develop better sipping hardware and is trying to upgrade the sipping equipment and still hold the cost down. Dry sipping was performed at one BWR by Company F in 1965.		55-79(v)*	Company F considers the efficiency to be <50% for in-core sipping and 90% for out-of-core sipping.(w)	

* Rate may be as low as ~193/14 = ~14 bundles/day.

TABLE 7.1. (contd)

Company	Sipping Technique	Requirement	Typical Rate No. of Fuel Bundles/Day	Approximate Leaker Detection Efficiency	Comments
G	Fuel has not been sipped by Company G at one PWR. That PWR does not have the equipment to perform detailed inspections of fuel at a poolside setup.				(r) Out-of-core dry sipping is not recommended by Company D for two reasons: (1) cost--extra equipment is needed and Company D does not think it is justified--and (2) data acquisition and interpretation difficulties (note that no leaker detection efficiency is listed by Company D).
H	Company H has never made plans to sip any fuel at one PWR and possesses no inspection equipment, other than closed circuit television (CCTV).(y)				(s) Company E has used a leak tester but does not routinely use it because, based on coolant activity, there is no need to leak test.
					(t) Company E said that leak testing (sipping) is slow, laborious, and very time consuming. If one had to leak test all the fuel from a PWR [this could presumably mean up to 193 fuel bundles], it could add up to two weeks to an outage.
					(u) Company F doesn't do in-core sipping at one site with BWRs for two reasons: in-core sipping is less effective than out-of-core sipping in identifying leaky fuel, and (2) the whole core is usually taken out anyway (about 7-9 days are required to unload the core).
					(v) Company F indicated it would take 7-10 days to sip 550 fuel bundles (assumes using six cans and doing some resipping). They use 8- and 10-hr shifts and expect to sip 40-50 fuel bundles per snift.
					(w) Company F says sipping effectiveness depends on the power history of the core.
					(x) The present system is simpler than the previous one used by Company F at one site with BWRs and reduces operator exposure because there are no valves to be manually operated. There are no automatic timers; timing and sipping sequence are manually controlled. With equal soak and count time intervals, optimum equipment usage is obtained.
					(y) No plans to sip fuel were made because the levels of radioactivity in the effluent during reactor operation have been low.

* Rate may be 550/(7 to 10) = 55 to 79 bundles/day.

TABLE 7.2. Comparison of Characteristics of Sipping Systems in Current Use[a]

Company	Sipping Technique	Bottom of Isolating Container (Can or BWR Channel)	Type of Seal at Top of Container	How is Contained Contaminated Water (Spent Fuel Pool Water or Primary Coolant) Displaced	Soak Period	Is Contained Water Recirculated	Volume of Sample(s)	Water and/or Gas Sample Analysis and Comments
A	This company offers a sipping system of own design as NSSS option.[b]							
A	Out-of-core wet and hybrid sipping (using a Company I system)				Maybe 1 hr			
B	Out-of-core wet sipping	Can bottom open	Inflatible seal (pneumatic system used to close lid and inflate seal).	Pool water is used for sipping			Two water samles, 250 ml each	Ge(Li) detector used; water sample analyzed for 3 isotopes, one of which is iodine-131. One water sample is stored.
B	In-core dry sipping[b]							
C	This company does no sipping themselves at reactor sites.[b]							
D	In-core wet sipping (four bundles sipped simultaneously)	Channel bottom not closed off	A "sipper head" that fits over a four-bundle cell is used.	Air used to lower contained primary coolant to top of fuel bundle.	~15-20 min	Mechanical mixing (pumping not used; decay heat used to thermally mix the contained coolant.	One-liter water sample taken. Of that sample, 200 ml is used for analysis.	Water sample processed radiochemically (gamma can) and analyzed for iodine-131 (considered as primary indicator of leakers) and iodine-132. Analysis for cesium-134 and cesium-137 is optional (cesium considered as secondary indicator; hence, analysis is not routinely done.)
D	Out-of-core wet sipping	Enclosed can		Forced circulation flushing with demineralized water is used	~30-60 min (typically 60 min; however, 45 min used at some plants and one plant used 30 min	Mechanical mixing used	One-liter water sample	Water sample processed radiochemically (gamma scan) for iodine-131, cesium-134, and cesium-137.
D	Out-of-core vacuum sipping (pressure differential gas sipping) at BWRs; however, this			Can flushed with demineralized or reclaimed (condensate) water and air sparged to reduce background. Then level of	~3-10 min (during soak period entire system is	Mechanical circulation is employed	Need for sample acquisition and laboratory analysis elimated by using on-line	Gaseous activity (i.e., krypton-85, xenon-133, and xenon-131m) is measured with an on-line beta scintillation

TABLE 7.2. (contd)

Company	Sipping Technique	Bottom of Isolating Container (Can or BWR Channel)	Type of Seal at Top of Container	How is Contained Contaminated Water (Spent Fuel Pool Water or Primary Coolant) Displaced	Soak Period	Is Contained Water Recirculated	Volume of Sample(s)	Water and/or Gas Sample Analysis and Comments
	equipment has been designed to also be used on the reactor vessel guide rods at BWRs.			contained water is lowered with air to top of fuel bundle	reduced in pressure by drawing a partial vacuum over the air/water interface)		detector. It has been demonstrated during development work on this technique that grab samples of water are significantly enhanced by the partial vacuum.	detector. Krypton-85 is considered as the primary indicator of leakers. If the fuel bundle has had a long decay time (i.e., years after being discharged from reactor core), the gas sample is only examined for krypton-85.
D	Out-of-core dry sipping (this company does not recommend this technique;[b] however, it is presently used at three small BWRs).			At one BWR, the water is exhausted from the can by pressurized air.	One BWR uses ~20 min for early discharges and to around 45 min for the last fuel bundles tested.			At one BWR, a CP monitor placed next to the charcoal trap of the sipping system provides an immediate qualitative indication of fuel bundle condition. Analysis of the gas sample, however, yields the quantitative and final classification of all the tests.
E	Updated version of a sipping system is being evaluated.							
E	Out-of-core wet, dry or hybrid sipping (using the leak detection system that is a part of a portable fuel inspection system) has been used in past;[b] if necessary, can also perform these inside reactor containment vessel. Hybrid (combination wet/dry)method is normally used.	(c)	(c)	When hybrid sipping, pool water forced from leak test chamber by nitrogen; chamber is then immediately backfilled with demineralized water. A background water sample is obtained from inside the chamber; water level in chamber is then lowered to top of fuel bundle; then nitrogen pressure above fuel bundle is reduced.	30 min	After soak period is over and gas sample taken, water is added to chamber in area above fuel bundle and recirculated; then water sample is taken.		The gas sample is collected by purging gas sample container. The water sample is analyzed for iodine isotopes.
F	Out-of-core wet sipping (using a Company J system)			Can is flushed for 15 min with dimineralized water.	Minimum soak time is 20 min		One-liter water sample	A CP is used to initially check the samples to get a general of the activity levels associated with leaky fuel bundles; unfiltered samples are checked first, then filtered samples (the millipore filter removes crud) are

TABLE 7.2. (contd)

Company	Sipping Technique	Bottom of Isolating Container (Can or BWR Channel)	Type of Seal at Top of Container	How is Contained Contaminated Water (Spent Fuel Pool Water or Primary Coolant) Displaced	Soak Period	Is Contained Water Recirculated	Volume of Sample(s)	Water and/or Gas Sample Analysis and Comments
								checked. A Ge(Li) detector and a multichannel analyzer are used to analyze the water sample for iodine-131 and cesium-137. Iodine-131 is their primary sipping isotope but has a short lifetime, making it necessary for them to look for their secondary sipping isotope, cesium-137. In some cases, however, cesium-137 is more sensitive than iodine-131 in identifying leaky fuel and thus will be used as the primary isotope. Usually, only one isotope is followed, although Company F has been encouraged by Company D to look at a number of isotopes. Spent fuel pool water samples are taken once per 8-hr shift and analyzed to determine background activity changes. After analytical results are obtained, the operator disposes of all the water samples.
G	Fuel has not been sipped by this company at this PWR because no fuel problems have been experienced in any of the associated fuel cycles.							
H	Activity levels have been low; hence, no plans for sipping have been made yet for this PWR by this company.(b)							

(a) The characteristics shown came from discussions during NRC-PNL visits to five fuel vendors and three reactor sites and from associated literature sources.
(b) See Table 7.1 for additional details.
(c) Each fuel bundle was individually tested under water in a test chamber.

7.2.2 Minimum Indication Required

It is not clear what minimum burnup might be needed to provide a sufficiently high radioactivity to detect a leaky fuel bundle by sipping. One fuel vendor estimated it might be about one month of irradiation.

Complete functional testing of dry sipping equipment in a spent fuel storage pool was performed at one BWR with an irradiated fuel bundle that had negligible decay heat (Ref. 8). That fuel bundle had a burnup of 21.6 GJ/kg of heavy metal (250 MWd/T) and had been out of the reactor for over two years.

As noted previously (Section 7.1.3.4), a gaseous release from a defective fuel rod of less than one microcurie is considered to be a low level of activity. Reference 18 indicates that a hybrid sipping system used by a foreign company has a sensitivity of 10^{-5} μCi/ml for direct measurement made with gas circulation (i.e., dry sipping).

7.2.3 Space Requirements, Operating Environment Limits, and Personnel Needs for Sipping

Space requirements for in-core and out-of-core sipping are indicated in Table 7.3. Some operating environmental limits for sipping are listed in Table 7.4.

For out-of-core wet sipping at one nuclear power station with BWRs, the utility indicated that up to approximately 8-10 people/shift or as many as 20 people/day can be involved. In the case of dry sipping, at one BWR (Ref. 74) the full-time services of three men were required, and at a second BWR (Ref. 8), five men were needed whenever a fuel bundle was in the sipping can with the lid in place.

Results of a study of the annual costs associated with 14 cost elements (one of which is sipping) at BWRs and PWRs as a function of fuel failure level have been recently published (Ref. 92). For end-of-cycle indicated fuel failure levels to ~500,000 μCi/sec in BWRs and to ~0.4% failed fuel in PWRs, the annual cost of sipping is the second highest among the 14 cost elements (the highest is the cost of lost burnup).

TABLE 7.3. Examples of Space Requirements for Sipping

Sipping Technique	Space Requirement: In-Core	Space Requirement: Spent Fuel Storage Pool	Space Requirement: Poolside Deck Space	Other Space and/or Comments
In-Core Wet Sipping	See Figure 7.3	--	--	A typical sampler fits over four BWR fuel bundles (i.e., a control rod cell).
In-Core Dry Sipping	--	--	--	One company's system has one sipping can in the fuel handling machine.
In-Core, Rapid-Sort System	--	--	--	One company's rapid-sort system has two basic components, the sensing head and the monitoring and data taking console. The sensor is mounted directly on the fuel grapple of the refueling machine and is connected to the console by a coaxial cable. The console is located on the floor overlooking the reactor cavity.
Out-of-Core Wet Sipping	--	1.7 m^2 (18 ft^2) [0.9 m x 1.8 m (3 ft x 6 ft)]	8.9 m^2 (96 ft^2) [2.4 m x 3.7 m (8 ft x 12 ft)]	One company used their own counting equipment when sipping; the equipment and its operation required a room 3 m x 3 m (10 ft x 10 ft). The room temperature has to be controlled and the room has to be away from poolside to avoid the background problem.
Out-of-Core Sipping (Water or Gas Analysis)	--	~0.21 to 0.30 m^2 (~2.3 ft^2)/BWR sipping can unit; (~3.3 ft^2)/ PWR sipping can unit		Deck space is required for operating personnel and for the control console, pumping station, and other equipment.
Out-of-Core Wet or Dry Sipping	--	--	>0.5 m^2 (>5 ft^2)	One company's bulletin shows a single fuel bundle container in the spent fuel storage pool. Deck space for operating personnel and for the pumping package would be needed in addition to the ~0.5 m^2 (~5 ft^2) for the control console.
Out-of-Core Wet or Combination Wet/Dry (Hybrid) Sipping	--	1.7 m^2 (18 ft^2) [0.76 m x 2.1 m (2.5 ft x 7 ft)]	>2.4 m^2 (>26 ft^2) [0.51 m x 4.6 m (>1.7 ft x 15.5 ft)]	These are the space needs for the five-can system shown in Figure 7.2. Deck space for operating personnel would be needed in addition to the ~2.4 m^2 (~26 ft^2) required for equipment.
Out-of-Core Vacuum Sipping	--	See Figure 7.10	>1.3 m^2 (>14 ft^2)	The sipping container is in a control rod blade storage rack. Deck space for operating personnel would be needed in addition to the ~1.3 m^2, (~14 ft^2) required for equipment.

TABLE 7.4. Examples of Operating Environmental Limits for Sipping

Parameter	Limit or Range
• Air:	
Temperature	Maximum: 325K, 52°C, or 125°F (Ref. 77) Minimum: 283K, 10°C, or 50°F (Ref. 77)
Relative Humidity	Maximum: 100% (Ref. 77) Minimum: 12% (Ref. 77)
• Pool Water:	
Temperature	Reference 67 indicates 283-352K (10-79°C or 50-175°F). Reference 77 indicates 305-311K (32-38°C or 90-100°F). Reference 93 indicates that bulk water temperatures are normally 293-323K (20-50°C or 68-122°F); however, operating specifications allow higher temperatures, in some cases to 373K (100°C or 212°F); in a few cases pools have operated below 293K (20°C or 68°F).
pH	Reference 77 indicates 6.0-8.0. Operating BWRs and independent spent fuel storage pools range from 5.3 to 7.5 and operating PWRs range from 4.5 to 6.0; however, onsite spent fuel storage pool specifications allow wider limits (Ref. 93).
Water Chemistry	Reference 93 indicates that while onsite spent fuel storage pool operating specifications allow wider limits, the operating water chemistries are as follows: BWRs and independent spent fuel storage pools use O_2-saturated, deionized; PWRs use O_2-saturated, borated, deionized water. Chloride specifications are generally <0.5 ppm.
Boron Concentration	Reference 93 indicates 2000 ppm boron as boric acid. One fuel vendor indicated that borated water at PWRs is a harsh environment.
Electrical Conductivity	Maximum: 5 μmho/cm (Ref. 77) Normal: 1 μmho/cm (Ref. 77)
• Radiation Fluxes From Fuel (Ref. 93):	
Neutron	$\sim 10^5$ n/cm^2-sec (>1 MeV) } (decreasing exponentially)
Gamma	$\sim 10^6$ R/hr } (decreasing exponentially)
• Background Radiation	The iodine-131 level in the reactor water is very important with respect to sipping test performance and to pool area accessibility (Ref. 83). At one foreign BWR, an activity concentration of less than 10^{-2} μCi/cc must be maintained if in-core wet sipping is to be conducted (Ref. 88). One fuel vendor indicates that the lower the background, the better the leak detection efficiency is for sipping; however, the background in the pool may not remain constant during sipping (e.g., because of fuel shuffling).

7.3 Accuracy and Precision of Sipping Data

7.3.1 Leaker Detection Efficiency, Reproducibility and Standards (Baseline Data), and Cross-Correlation of Sipping Results with Other Inspection Results

7.3.1.1 Leaker Detection Efficiency

Leaker detection efficiency is the ratio of leaking fuel detected to leaking fuel present. Data on leaker detection efficiencies for the various sipping techniques are listed under "Approximate Leaker Detection Efficiency" in Table 7.1. Information on leaker detection efficiencies can also be found in References 14, 18, 66, and 79.

In the United States, out-of-core wet sipping and combination wet/dry (hybrid) sipping of BWR and PWR fuel are generally regarded as having a leaker detection efficiencies of 90 to 95% or greater. One foreign company assumes the leaker detection efficiency with PWR fuel to be over 99% (Ref. 18); their recent experience at two PWRs (Ref. 14) indicates it to be 100%, based on the decrease in fission-product activity in the reactor coolant at the start of reactor operation. Measuring primary coolant activity during startup after refueling is one method for evaluating the success of a sipping test; however, the primary coolant cleanup system can affect the results.

Early studies (1965-1967) at some of the smaller, older BWRs found wet sipping to be time consuming. Erratic results were often produced, especially with fuel bundles that had relatively small defects (the wet sipping technique was unable to discriminate between a small defect in the fuel rod cladding and radioactive iodine contamination on the fuel bundle surfaces). The studies also showed that in-core wet sipping yielded indications of cladding failures but did not conclusively identify leakers.

Recent studies by one fuel vendor show that, in general, in-core wet sipping of BWR fuel by an older technique can have a leaker detection efficiency of 60 to 80%. At one nuclear power station with BWRs, the associated utility indicates that it considers in-core wet sipping at present to have a leaker detection efficiency of less than 50%. With one fuel vendor's new technique, in-core wet sipping of BWR fuel can currently have a leaker detection

efficiency of 80 to 100%. That vendor recommends this technique because the efficiency is high and no fuel movements are required.

One foreign company uses in-core wet sipping on BWR fuel and has never used out-of-core wet sipping because they feel the latter takes too much time. They estimate that the leaker detection efficiency of in-core wet sipping is about 80% when the iodine-131 concentration in the reactor water is 10^{-2} μCi/ml (Ref. 14).

No leaker detection efficiencies for in-core or out-of-core dry sipping were located in the information collected to date. Dry sipping is presently used at three small BWRs (Big Rock Point, Humboldt Bay-3, and LaCrosse) and some of the large PWRs currently have in-core dry sipping systems. At present, one fuel vendor does not recommend out-of-core dry sipping of BWR fuel because of cost and difficulty of data acquisition and interpretation.

One fuel vendor's out-of-core vacuum sipping technique has a leaker detection efficiency of more than 95% with BWR fuel.

7.3.1.2 Reproducibility, Standards (Baseline Data), and Cross-Correlation of Sipping Results with Other Inspection Results

At one nuclear power station with BWRs, the utility's sipping analysis is based on relative activity levels of a group of sipped fuel bundles. Results of sipped bundles are not compared against standards; however, an energy calibration using button sources is performed to identify the location of isotope peaks. Sipping results using relative activity levels are achieved by using identical handling, sipping, and counting procedures for each fuel bundle and completing the sipping before the decay of the isotope(s) of interest is significant. The utility indicated that the precision of the counting was very good (~2%). On accuracy, they said the results from leaky fuel bundles probably had a fairly wide range, possibly ±50%.

In the analyses of their samples from sipping tests on PWR fuel, another fuel vendor corrects for half-life, efficiency, abundance, and baseline pool isotopic activities. The statistical analysis of the activity data is performed by computer. Among the fuel vendors and utilities, this fuel vendor is the only one found in this survey that stores a duplicate sample.

Two of the fuel vendors said they could not really comment on the accuracy and precision associated with their sipping results.

A campaign to detect leaking fuel bundles by the wet sipping method was conducted at a PWR during a July 1974 shutdown (Refs. 71 and 72). Visual inspection identified a total of 18 defective fuel rods (all but one attained burnups higher than the core average) in 10 of 12 fuel bundles with sipping indications. In 1975, at that same PWR, fuel bundles were again examined for failed fuel rods by the wet sipping method and resipping of two fuel bundles clearly demonstrated the reliability of the wet sipping technique in identifying failed fuel and the capability of resipping (Ref. 73).

Leaker detection efficiencies for sipping techniques have been determined by one fuel vendor by:

- Comparison of sipping results with nondestructive examination results (i.e., from eddy-current and ultrasonic tests; however, they do not consider these as primary examination results)
- Comparison of sipping results with data from off-gas analysis
- Cross-correlation with the results from other sipping tests (e.g., comparison of data from in-core and out-of-core sipping tests).

This fuel vendor estimated that they have disassembled about 1000 sipped fuel bundles and nondestructively examined (with eddy-current and ultrasonic tests) the fuel rods. Their experience has shown no correlation between sipping results and the size of the fuel rod cladding perforation.

At one PWR, the associated utility reports that most sipped fuel bundles with iodine-131 activities greater than 10^{-2} μCi/ml exhibit visual evidence of cladding failure (Ref. 30).

At one nuclear power station with BWRs, the utility has found in the past that if the activity of the sample from the sipping system is greater than three times that of the background, they find visual and/or eddy-current indications of failed fuel rods.

Another fuel vendor has taken four fuel bundles apart and found (by visual means) one leaking rod in a fuel bundle that gave a sipping indication. They also found no leaking rods in those fuel bundles that gave no sipping indications.

In-core wet sipping of fuel bundles at a BWR in 1966 indicated two probable failures and eight suspects (Ref. 74). Visual inspection of one of the least suspect fuel bundles (this bundle had a relatively low sipping signal and low burnup) revealed a gross failure of one fuel rod--about eight inches of fuel was missing. Visual inspection of 30 previously sipped fuel bundles [burnups were greater than 605 GJ/kg of heavy metal (7000 MWd/T)] revealed that four bundles had gross defects (one had five failed fuel rods; one had two failed fuel rods with approximately 76 mm (3 in.) of fuel missing from each rod).

Wet sipping was used to identify three failed fuel bundles [mean burnup was 1285 GJ/kg of heavy metal (14,870 MWd/MTU)] at a foreign BWR (Ref. 94). Other inspection techniques that were used to confirm that seven failed fuel rods were present in those bundles included: eddy-current testing, visual inspection, a coarse leak test (dry sipping for krypton-85), and fission gas sampling.

Based on curves of off-gas activity of krypton-85 and xenon-135 as well as reactor coolant activity of iodine-133 and neptunium-239 versus time, it was assumed that a small leak developed at a foreign BWR during late 1972 (Ref. 75). Fifty of the fuel bundles were systematically selected for leak testing. A single bundle was found to be leaking; the leak was confirmed by visual inspection.

At one BWR, visual confirmation of failures in fuel bundles classed as positive leakers by dry sipping was obtained on a representative sample (Ref. 76).

7.3.2 Hardware Limitations

Studies at a BWR in 1965 on wet sipping indicated that it was a time-consuming technique, which required a considerable effort on radiochemical laboratory analysis and particular care in sampling to prevent contamination of personnel and equipment (Ref. 8). At another BWR in 1966, some fuel bundles with gross defects in fuel rods were not detected by in-core wet sipping (Ref. 74).

In some sipping operations in the past, personnel had to use long-handled [9.1-10.7 m (30-35 ft)] wrenches while reaching over valves and motor controls, which resulted in low fuel bundle throughput rates at the sipping station and undesirable radiation exposure. In comparison to those cases, one sipping equipment brochure indicates that improved equipment has reduced sipping times by 50-75% and lowered radiation exposure to personnel by a factor of 10 to 100.

Sipping installations currently range from manually operated to fully automated equipment. The equipment currently used by the utility at one nuclear power station with BWRs employs manual operation through a control console (fluid actuators). The present system is simpler than the previous system and reduces operator exposure since there are no valves to be manually controlled. With the current system, an operator is required to pull the sample and then transport it to the counting room, located on another building floor. One potential problem indicated by the utility with the present system is possible spillage during sampling.

The wet/dry sipping equipment used by the utility at one nuclear power station with PWRs is reported to have proved to be fast and reliable; it identified every fuel bundle with visible defects, except for one (Ref. 30). That one bundle had a grossly failed fuel rod (hence no volatile fission products were retained in the rod). With this equipment, radiation levels at the wet sipping console have ranged from 10 to 100 mrem/hr, depending on the type of crud on the fuel bundle and the time since reactor shutdown; however, flushing the lines with demineralized water caused the levels to rapidly drop to a background of 10 mrem/hr. Some fuel with unusually heavy crud deposits (made the water turn black) caused radiation levels to reach 1000 mrem/hr on contact with certain parts of the wet sipping console. Operational problems with the equipment are described in Reference 30; most were not serious enough to stop sipping operations. Steel shielding is used around the sipping container cover seal to minimize radiation damage (Ref. 78).

One fuel vendor has vacuum sipping equipment that is fully automated, which reduces manpower needs and personnel exposure. It also has the potential for reducing the critical path time required for fuel sipping.

Another fuel vendor stated that the current sipping time constraints are not due to the sipping equipment but are due to the PWR fuel handling requirements. With their sipping concept, it is possible that sipping could be done over a standard PWR fuel rack position. New high density fuel storage racks may present some additional mechanical interface problems.

In general, the sipping rate is dependent on operating restrictions on reactor plant equipment (e.g., for fuel bundle handling), in addition to other factors (e.g., type of sipping equipment, fuel burnup, time since reactor shutdown, and nature of crud deposits). One fuel vendor pointed out that the spent fuel pool cleanup system and reactor cleanup system are run at full capacity to keep the background down during sipping. With wet sipping, leaching of fission products is the controlling process rather than radioactive decay; as a result, wet sipping needs to be done within a few weeks after reactor shutdown (Ref. 64).

At one PWR, a minimum detectable activity level (MDA) was defined and if the net fuel bundle activity, as determined by sipping, was less than the MDA, the net fuel bundle activity was set equal to the MDA (Refs. 71-73). Experience at that reactor indicated the MDA would be about 10% of the measured pool water background level (Ref. 73).

Fuel rod cladding temperature is currently not measured during sipping; however, it is typical for the temperature of the water or gas in the sipping can to be measured. Fuel rod cladding temperature during sipping has been measured in studies that are described in Section 7.3.4.

Malfunctions with poolside inspection equipment are not uncommon. One utility indicated, for example, that equipment malfunctions may produce a count well below the average count level from nonleaking fuel bundles.

One utility stated that when they analyze sipping samples, the temperature of the sample counting room has to be controlled and the room has to be away from poolside to avoid the background problem.

Excessive crud release can result in poor visibility. At a foreign BWR, this hindered the in-core sipping operations because the sipping head could not be positioned properly above the fuel cell and resulted in sipper tubes being bent (Ref. 79).

Fuel bundles with very low burnups or long decay times are special cases. Several foreign companies use additional electric heating to shorten the soak period and increase the final temperature (improving test reliability). One foreign company has reduced the water sample size (to 50 ml) from in-core wet sipping at BWRs so a direct measurement is possible without intermediate process stages (Ref. 18). This reduces personnel exposure and the risk of contamination during sampling.

7.3.3 Time Requirements

Typical sipping rates are listed in Table 7.1. Information on sipping rates may also be found in References 8, 14, 16, 18, 66, 71, 72, 74, 80, 82, 83, 90, and 91. In those sipping tests that involve a heatup (soak) time, the goal is to establish a minimum soak time (so thermal shock effects on the fuel can be minimized) that will yield acceptable signal levels (Ref. 8). Typical soak times can range from ~3 to 60 minutes. The soak time may either be a variable period that is dependent on a measured temperature or a predetermined fixed period (Ref. 16). The sipping procedure used by the utility at one domestic nuclear power station with BWRs is designed around minimal counting time, and the counting time is approximately equal to the soak time. With equal soak and count time intervals, optimum equipment usage is obtained. In tests at a BWR, the results indicated that the sip signal was essentially independent of soaking times between 5 and 20 minutes (Ref. 8).

At domestic plants, out-of-core wet sipping is normally conducted within a few days after the reactor is shutdown for a refueling outage. Dry sipping at two BWRs (Humboldt Bay-3 and Elk River) has begun as early as two to three days after reactor shutdown (Refs. 8 and 74).

In European BWRs, in-core wet sipping is usually done during the period of one day to one week after reactor shutdown (Ref. 65). At one foreign BWR, the utility feels that in-core sipping seems to be effective in at least 90% of the cases if it is performed within one week after reactor shutdown and if the reactor has operated near to full load for at least two weeks (Ref. 95). At another foreign reactor, testing of fuel with out-of-core hybrid sipping equipment is apparently underway one week after reactor shutdown (Ref. 18).

7.3.4 Factors Affecting Overall Accuracy

Sipping is one of the more accurate methods for checking fuel bundle integrity. However, sipping is not an exact diagnostic method for detecting leaky fuel bundles, as it can have a tendency to identify leakers that occur late in the reactor cycle (see Section 7.4.3).

Cladding temperature is not measured during sipping in any of the techniques currently in use. Pool water temperature is measured during sipping and generally the temperature of the air or water in the sipping container is also measured. At least one domestic BWR does not measure the temperature of the water in the can when out-of-core wet sipping. Cladding temperatures have been measured during dry sipping on at least seven fuel bundles: at one BWR (Refs. 8 and 80), a spring-loaded thermocouple probe showed that air space temperature during dry sipping closely followed the cladding surface temperature of an outer fuel rod, and at another BWR (Ref. 74) the air temperature consistently followed the cladding temperature in the six fuel bundles tested. In the latter case, the investigators found that cladding failures were readily detectable when the cladding surface temperature was 339 K (150^{o}F), as measured by a thermocouple.

One fuel vendor indicated that the lower the background, the better the leaker detection efficiency. However, the background may not remain constant during sipping. One utility indicated that during their out-of-core wet sipping at one nuclear power station with BWRs, the effect of the background is known and is taken into consideration when analyzing the results since fuel pool samples are taken once per 8-hour shift and analyzed for activity changes, but this background activity may vary as spent fuel is placed or moved in the storage pool.

With out-of-core wet sipping, one fuel vendor indicates that the leaker detection efficiency is somewhat dependent on the decay heat (for the leaching process only) and is independent of reactor coolant background. In comparison to incore wet sipping, out-of-core wet sipping has the advantages of forced circulation flushing with demineralized water to expel the pool water from the

sipping can (reduces residual contamination) and the absence of reactor background. One of the fuel vendors performs out-of-core wet sipping with pool water.

The leaker detection efficiency of in-core wet sipping was indicated by one fuel vendor to be dependent upon the decay heat (it affects the mixing of and leaching by the contained coolant) and the background (i.e., the iodine-131 concentration in the reactor coolant). Because deviations are measured against it, the background radiation is a factor to be considered since the contained coolant comes from the reactor primary coolant and has been associated with all the fuel bundles (leakers and nonleakers).

Dry sipping is a useful technique when fission product release is relatively small (Ref. 15). Lengthy radiochemical analyses are not needed and the identification of fuel bundles with significant defects in the fuel rod cladding is definite as a sharp distinction is observed between sound and defective fuel (Refs. 74, 76, and 81). However, there can be some difficulties with the dry sipping technique (see Table 7.1).

The leaker detection efficiency of out-of-core vacuum sipping technique is indicated by one fuel vendor to be independent of decay heat and is independent of reactor coolant background. In comparison to wet sipping techniques, data analysis with vacuum sipping is simplified because an on-line detector is employed.

LWRs typically use a "relative" analysis sipping program in which each fuel bundle in a group is handled and sipped identically (e.g., a fixed soak period is used). A normal activity level (i.e., a background level in relation to leaking fuel) is established for the group of fuel bundles that have been sipped. From an operational viewpoint, a fixed soak period is simple to use; however, it makes the detection of leakers difficult when irradiation and cooling histories vary widely among the fuel bundles to be sipped (Ref. 16). Because relative measurements are involved, fuel bundles yielding "abnormally" high signals can only be identified after sipping has been underway for some time.

In classifying sipped fuel bundles (e.g., selecting those for resipping), knowledge is needed on the fuel bundle sipping sequence--carryover of contamination can occur if a leaky fuel bundle preceded the given fuel bundle in the same sipping can--and on the statistical information (sip signal-to-background ratio) for sound fuel bundles of the given batch. Factors that affect the resip threshold for fuel batches include burnup and crud level.

At one nuclear power station with BWRs, the utility indicated that if a leaky fuel bundle is detected during sipping, the can is flushed with clean demineralized water. Occasionally the sipping can becomes contaminated from a leaky fuel bundle and an "echo" effect is produced (i.e., the can contributes activity when other fuel bundles are subsequently sipped, which may be as much as three times the established background for a nonleaking fuel bundle). With an equalized soak and count time cycle, the count results are not known until later when the sample is counted on the analyzer. Residual activity from an incomplete flushing of the sipping can affects the results for the next two to three fuel bundles to be sipped in that can. Resipping is usually done to resolve ambiquities from these "echos," to re-verify that fuel bundles do or do not contain leaky fuel rods, and to identify equipment malfunctions which may produce a count well below the average count level from nonleaking fuel bundles.

At one PWR, the utility found, in general and whether or not a fuel bundle contained failed fuel, that some level of iodine-131 activity above the minimum detectable activity level (MDA) was associated with each fuel bundle (Ref. 73). They defined MDA as the net fuel bundle activity, which is the fuel bundle water sample activity less the baselines (i.e., the concentrations of each isotope in the water in the sipping can before insertion of a fuel bundle into the can). Experience at that PWR indicated that the MDA would be about 10% of the measured pool water background level (Refs. 71 and 72). They believe as a result that the scatter in their sipping data for a certain group of fuel bundles represents real differences in the iodine-131 concentrations associated with each fuel bundle. They concluded that the iodine-131 was most likely contained in the crud deposits on the fuel rods or structural components of each irradiated fuel bundle and that the cesium was apparently not associated

with the crud. They also concluded that the cesium concentrations exceeded the MDA limit only when the measured sample was associated with failed fuel or sipping can contamination.

Out-of-core sipping at some foreign PWRs involves insulated sipping cans that allow the contained water to boil, which increases the expulsion of fission products and increases leaker detection efficiency (Ref. 18). Two foreign papers (Refs. 96 and 97) indicate that warm water injection can improve leaker detection. The improvement results from flattening the axial temperature distribution in the fuel bundle.

7.4 Analysis of Sipping Data

7.4.1 Typical Results

The following is one example of how results from wet sipping of fuel from one domestic PWR were obtained (Ref. 73). A water sample from the sipping apparatus was analyzed for the three isotopes (iodine-131, cesium-134, and cesium-137) by counting their respective gamma rays by means of a Ge(Li) detector and a multi-channel analyzer system. The concentration of a given isotope in the water sample (in μCi/ml) was established by correcting the number of gamma ray counts in the appropriate peak for background, efficiency, abundance, half-life, and sample volume. The measured concentration of each isotope for unfailed fuel bundles yielded log normal distribution curves. As discussed in the following section, a criterion to distinguish between fuel bundles that did or did not contain leaky fuel rods was established, based on past experience and the evaluation of results from that sipping campaign.

Typical isotopes used as reliable indicators of fuel failure are shown in Table 7.2. Information on isotopes used may also be found in References 8, 14, 66, 71-73, 75, 76, 79, 81, 83, 84, 89, 90, and 91. The isotopes measured differ, depending on whether a water or gas sample is involved. Iodine-131 (half-life is ~8 days), iodine-133 (half-life is ~1 day), xenon-133, and xenon-135 were evaluated separately in a study (Ref. 98). The investigators concluded that less uncertainties were associated with the use of iodine and that iodine-131 will be the dominant isotope for small cladding defects.

With out-of-core sipping, water samples are typically analyzed for iodine-131, cesium-134, and cesium-137. At one domestic PWR, the utility considers all three of those isotopes as reliable indicators of leaking fuel (Refs. 71-73). At one domestic nuclear power station with BWRs, the utility usually follows only isotope: iodine-131 is used as the primary indicator. They may use cesium-137 as a secondary indicator, but in some cases cesium-137 is more sensitive than iodine-131 and is then used as a primary indicator. At one foreign BWR, both cesium-134 and cesium-137 proved to be equally effective in identifying leakers, even after the discharged fuel bundles had been stored for extended time periods (Refs. 14 and 99).

Figure 7.12 is an example of the resolution presently achieved by a foreign company with their PWR out-of-core wet sipping technique (Refs. 18 and 99). Note the large margin between sound (leak tight) and leaking fuel bundles. That company has made several improvements in BWR in-core and PWR out-of-core wet sipping techniques. In the former case, they reduced the size of water sample to 50 ml, which allows direct measurement with no intermediate process stages. In the latter case, they added thermal insulation to the sipping cans, which permits the contained water to boil and thus increase the expulsion of fission products.

With in-core sipping, most water samples are analyzed for iodine-131 and iodine-132, and some are analyzed for cesium-134 and cesium-137. One domestic fuel vendor considers iodine-131 as a primary indicator of leakers and cesium-134 and cesium-137 as secondary indicators; they consider cesium isotope analysis as optional (as a result, it is not routinely performed). At one foreign BWR, it has found that iodine-131 was better than iodine-132 for identifying leakers, even 10 days after reactor shutdown (Ref. 79).

Gas samples can be analyzed for krypton-85, xenon-133, and xenon-131m. In dry sipping tests at a BWR in 1966, the maximum xenon-133 concentration in any of the vented gas samples was 1.25 μCi/ml (Ref. 8). This was an order of magnitude less than the concentration of fission gas in the off-gas system when the release rates were at the annual average limit of 50,000 μCi/sec. With vacuum sipping, one fuel vendor considers krypton-85 as the primary indicator of leakers and may also analyze for xenon-133 and xenon-131m. If there has been a long decay time (i.e., years after discharge), only krypton-85 is checked.

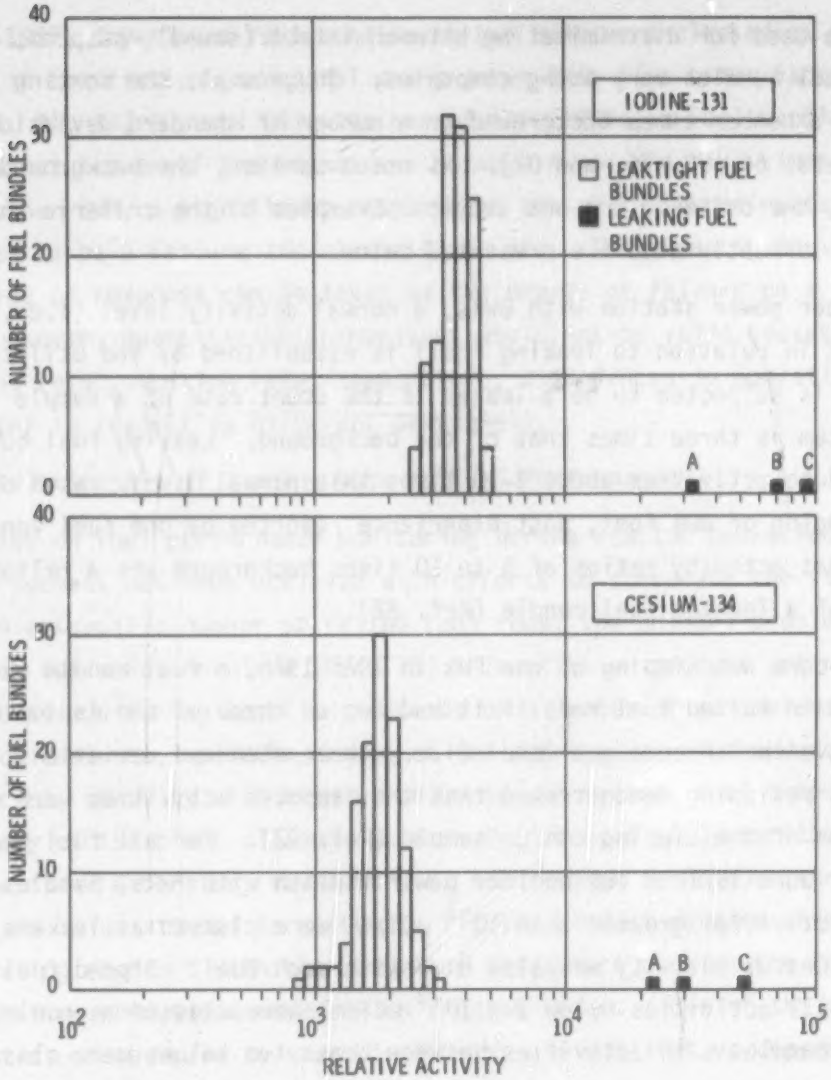

FIGURE 7.12. Frequency Distribution of the Relative Activity Concentrations of Iodine-131 and Cesium-134 Measured in Sipping Samples from PWR Fuel Bundles (Refs. 18 and 99)

7.4.2 Criteria for Discriminating Between Intact, Suspect, and Defective Fuel

One fuel vendor indicated that the utility sets the sipping criteria; however, the fuel vendor decides what constitutes a leaker. A lot of judgment is involved in defining what constitutes a leaker: the level for classifying a fuel bundle as a leaker is usually 10 times lower than that in the contract warranty.

The criteria used for discriminating between intact (sound), suspect, and defective fuel bundles vary among companies. In general, the sorting criteria can involve a number times background or a number of standard deviations above the mean (Refs. 64, 73, 76, and 82). As noted earlier, the background may vary; hence, the criteria are not static. Examples of the criteria that have been or are currently used are presented below.

At one nuclear power station with BWRs, a normal activity level (i.e., a background level in relation to leaking fuel) is established by the utility. A fuel bundle is suspected to be a leaker if the count rate of a sample from the sipping system is three times that of the background. Leaking fuel bundles usually produce activities about 3-10 times this normal level. With out-of-core wet sipping of BWR fuel, past experience reported by one fuel vendor has indicated that activity ratios of 5 to 10 times background are a reliable indication of a leaking fuel bundle (Ref. 82).

With out-of-core wet sipping at one PWR in 1975-1976, a fuel bundle was considered to contain failed fuel rods if it had two or three of the isotopic concentrations above the three-sigma level (i.e., three standard deviations above the mean) unless resipping demonstrated that the measured activities were due to contamination of the sipping can or sample (Ref. 73). For all fuel bundles sipped as of June 1977 at one nuclear power station with PWRs, bundles with iodine-131 activities greater than 10^{-2} μCi/ml were classed as leakers (Ref. 30). Cesium activity was also high with such fuel. Sipped fuel bundles with iodine-131 activities below 2×10^{-3} μCi/ml were classed as nonleakers. Sipped fuel bundles with activities between those two values were classified as "questionable" leakers.

In-core wet sipping at a foreign BWR indicated that the sipping test is a relative measurement of the sample activity in comparison to the average or background; hence, it was stated in a 1973 paper that no clear-cut boundary exists between sound, marginal, and defective fuel bundles (Ref. 84). Major defects, which were most likely hydride blisters (they did not perform any visual inspection), were believed to be present in 19 fuel bundles that had iodine-132 sip signals that were a factor of five higher than background.

In 1966-1967, dry-sipped fuel bundles at two BWRs were classed as positive leakers if the fission gas signal was greater than five times background (Refs. 8, 74, 78, 80, and 84). At one of those BWRs, a fuel bundle was defined as a suspect leaker if the signal was between three and five times background. At the other BWR, a significant response on two of the three radiation monitors was taken to be a failure indication (Ref. 74). The investigators stated that the degree of response can be taken as the degree of failure on a qualitative basis; however, quantitative comparisons would not be valid because of the many variables (e.g., venting rate, temperature, differences in operation, and variations in readout by different personnel).

7.4.3 Relationship of Sipping Data to Fuel Performance

In studies on fuel performance monitoring during reactor operation, only limited success has been achieved with efforts to correlate the fission product level to a specific number of failed fuel rods; the primary problem is the number of variables involved (Ref. 15). The fission product activity level detected at monitoring locations depends on a number of parameters including: number of failures, specific design of the plant, size of the defects, burnup, power level, quantity of "tramp" uranium in the system, fuel temperature, and efficiency of the plant cleanup system. In a recent study for the NRC, Oak Ridge National Laboratory reviewed U.S. and foreign techniques and facilities being used in an attempt to correlate fission product release characteristics in operating reactors with the nature of the defect causing the release and the operating conditions under which release occurs. One of the peculiar characteristics of observed releases in PWRs is the qualitative dependence of the iodine-131/iodine-133 ratio on defect size.

A report (Ref. 98) on a study by one fuel vendor does not contain comparative data on calculated and measured defect levels of PWR fuel, though there were indications that there could be a wide variance due to the assumptions employed. A report (Ref. 100) by one utility provides a comprehensive compilation of coolant activity and calculated defect level. It was concluded in the NRC report (Ref. 15) that industry still lacks an accurate technique to correlate measured activity at the reactor site with defect level.

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At a nuclear power station with BWRs, the utility indicated that if at the start of a reactor cycle the stack release is about 50,000 microcuries/sec and increases to about 80,000 microcuries/sec at the end of the cycle, they assume 5 to 7 or 8 holes in the fuel rods are present. They estimate that an increase of 3,000-5,000 microcuries/sec beyond the normal background usually indicated perforation of a single fuel rod in the operating core and release of the fuel rod off gas. From a gross failure of one rod, releases can approach 125,000 microcuries/sec. Flux tilting (i.e., changing the neutron flux profile across the core) helps in locating leaky fuel bundles and thus aids in the selection of those fuel bundles to be sipped. Knowing the off-gas constituents helps in classifying the leak type. The off-gas constituents depend on the leak size and leak penetration depth within the fuel pellet.

Sipping tests can preferentially identify cladding breaches that happen late in the reactor cycle (Ref. 13). Two things can interfere with the detection of old leaks by sipping tests: the cladding fissure can become closed because of crud or other buildup or the entire fission product inventory may not be readily available (due to less than perfect axial communication) for release.

In foreign studies (Ref. 14), sipping results confirmed that there seems to be a strong correlation between activity release during BWR operation and changes in fuel rod linear heat generation rate. The iodine-134 core release rate at full power appears to be a useful indication as to the number of failed fuel bundles.

7.5 Hazards to Fuel Integrity

Minor spacer grid damage [bottom strap on spacer grid nearest bottom of fuel bundle was displaced upward ~3 mm (~0.12 in.)] to one fuel bundle was observed at one BWR (Ref. 101). The damage is believed to have probably occurred as the bundle, when new, was inserted into a sipper-stripper(round pipe), the edges of which were not properly designed for receiving a stripped (i.e., a shroudless or dechanneled) fuel bundle. The spacer grid damage did not preclude proper installation of the channel on the bundle.

A significant disadvantage of dry sipping is the possibility of overheating or thermal shocking the fuel bundle if there is inadequate control of the temperature in the sipping container during sipping (Ref. 74). In 1967, it was concluded in studies at a BWR (Ref. 16) that there is no danger of causing damage to the fuel by thermally induced stresses (shock) if the cladding temperature rise is not permitted to go substantially above 478 K (400^{o}F).

When a BWR was brought to power after an outage in 1966, scale came loose from the fuel rods, lodged on fuel spacer grids, and increased fuel bundle spacer grid flow resistance (Ref. 8). A contributing factor to this abrupt scale spallation may have been the small thermal cycle effect involved in the dry sipping work performed on those fuel bundles during the outage.

In comparison to out-of-core wet sipping, there is less chance for damage to BWR fuel bundles during in-core wet sipping because no fuel movements are required and the fuel is encased in a Zircaloy channel (Ref. 64).

7.6 Summary and Conclusions

Sipping provides a quantitative measure of fuel bundle performance, especially for fuel that is grouped according to design and performance characteristics (Ref. 12). Sipping tends to be used routinely at domestic BWRs and tends to be used only if necessary at domestic PWRs. Sipping is one of the more accurate examination techniques for determining the integrity of the fuel, but initiating a fuel bundle sipping campaign with a predetermined threshold for defining leakers does not appear to be feasible. Sipping also illustrates why it is difficult to define failed fuel. Because sipping involves a relative measurement of the activity in the sample in comparison to the average (background), those fuel bundles with "abnormally" high measurements can only be identified after sipping has been underway for some time. The absolute magnitude of the sip signals can vary for a number of reasons, including: fuel bundle burnup, time since reactor shutdown, and crud level. In addition, the background does not remain constant. The leaker detection efficiency of in-core sipping is dependent on the reactor coolant background while that of out-of-core sipping is not. However, the background of the spent fuel storage pool water may vary as spent fuel is placed and moved around in the pool.

One fuel vendor stated that the utility sets the sipping criteria; however, the fuel vendor decides what constitutes a leaker. Criteria employed for discriminating between intact (sound), suspect, and defective fuel bundles vary among companies. In general, the sorting criteria can involve a number times background or a number of standard deviations above the mean (e.g., a bundle is classed as a leaker if the concentrations of two or three of the three specified isotopes are above the three-sigma level), with the latter being a more rigorous specification. A lot of judgment is involved in defining what constitutes a leaker: the level for classifying a fuel bundle as a leaker is usually 10 times lower than that in the contract warranty.

Sipping as a means of detecting leaky fuel bundles is not an exact diagnostic technique as it can preferentially detect fuel rod cladding perforations that occur late in the reactor cycle (Ref. 13). Fuel bundles with grossly failed fuel rods may not be readily identified by sipping. One fuel vendor's experience has shown no correlation between sipping results and the size of the fuel rod cladding perforation.

In comparing in-core and out-of-core tests (e.g., sipping), the in-core tests are generally less definitive because of the core's remoteness and the fact that it may be highly radioactive (Ref. 15). Out-of-core sipping is theoretically more effective than in-core sipping because of higher fuel temperature and lower environmental activity. Actual experience generally shows that to be the case. For example, the leaker detection efficiency of the newer in-core wet sipping methods tend to be 80% or greater while out-of-core wet sipping tends to be 90 to 95% or higher.

Fuel handling can be a constraint on the rate at which fuel bundles can be inspected by sipping. At BWRs, in-core wet sipping does not involve fuel handling while out-of-core sipping does. At PWRs, the in-core sipping system can be a part of the fuel handling machine; the out-of-core sipping systems involve fuel handling. European plants can sip faster than U.S. plants because they do not have to verify each fuel move.

In-core sipping always has the potential of being on the reactor outage critical path, but out-of-core sipping (a more time-consuming operation) is not

always considered a critical path item during an outage. It may be a critical path item if sipped fuel bundles are scheduled to go back into the reactor.

One fuel vendor's sipping concept for PWR fuel bundles involves sipping over a standard PWR fuel rack position. New high density fuel storage racks may present some additional mechanical interface problems.

8. MENSURAL INSPECTION

8.1 Poolside Mensuration

The primary use of poolside mensural data is evaluating new fuel designs and upgrading fuel design and performance codes. As a result, the fuel vendors have a much higher interest in poolside mensuration than the utilities. Poolside mensuration, therefore, is not usually a high priority item in a reactor outage, and a mensuration program may be modified or restricted to avoid becoming a critical path item. There are generic differences in nuclear fuel that affect the type of measurement data and tools used in poolside mensuration. BWR fuel bundles (in contrast to PWR fuel) have a fuel bundle channel, which is often the gaged subject. Because of the proprietary nature of fuel designs, fuel vendors consider mensuration data and even mensuration techniques that could potentially indicate a performance level or problem as proprietary information. Specific mensuration data can also provide some insight into the detailed nature of fuel vendor's proprietary fuel codes.

Because of the expense involved with poolside mensuration, only a few fuel bundles are selected for the full dimensional gaging sequence. These bundles may be dimensionally followed through several reactor cycles. As a rule, "new" fuel bundles are dimensionally inspected for a go/no go decision with respect to the fuel bundle design specifications, but these tolerances are normally considerably larger than the dimensional accuracy associated with measurements obtained in a typical poolside mensural inspection campaign. Cursory mensural data are obtained from simple visual inspection. These data are in the form of comments about the degree of shape change of an abnormal fuel system component [an example is the estimation of fuel rod-to-fuel rod (water channel) closure]. In the review of mensural inspection techniques, it was apparent that poolside mensural hardware and techniques are in a continual state of evolution. Most fuel vendors have tried (at least in the laboratory) almost all gaging techniques currently in practice that have potential for use at poolside, although they may use other approaches in their current mensural campaigns.

The design evolution has been directed at higher accuracies, minimized implementation effort and time, and more automation of data acquisition and processing. The newer mensural equipment is being designed to gather better data with less impact on the reactor outage.

8.2 Poolside Measurements

8.2.1 Measurement Parameters

Although almost every dimension of a fuel bundle has probably been measured during a poolside inspection campaign at one time or another, there are only a few physical parameters that are frequently gaged, as shown in Table 8.1. Not all of these parameters would be gaged in a typical poolside inspection. For example, fuel bundle twist and bow and fuel rod profile (where fuel rod OD and ovality are measured while the fuel rod is still in the fuel bundle) are not frequent poolside mensural tasks. Most of the mensural parameters (even individual fuel rod length and profile) are obtained from measurements on an assembled fuel bundle. The main incentive is to reduce the manpower and time requirements and, hence, to lessen any impact on the reactor outage critical path. A more subtle motivation is that the probability for potential handling damage also increases as the amount of fuel handling is increased. Therefore, there is a preference toward simple mensural tasks on fuel bundles rather than on individual fuel rods from a disassembled fuel bundle.

8.2.2 Poolside Mensural Inspection

For each poolside inspection involving mensural tasks, the type of hardware and mensural techniques used are unique. Mensural inspection is not used for the detection of failed fuel, but in the assessment of fuel performance and predictive fuel codes. In comparison to inspectors with other poolside inspection tasks, there is much more variance between inspectors with the poolside mensural tasks in the selection and emphasis of equipment and procedures for the various dimensional measurements to be performed. Table 8.1 summarizes some of the mensural parameters and the measurement accuracies claimed by fuel inspectors. This table does not show all of the measurements performed by an inspector but only measurements where accuracy data were published (e.g., Refs. 24,

TABLE 8.1. Poolside Mensual Parameter Accuracy

Measurement[a]	Data From Fuel Vendors				
• Fuel Bundle:					
Length, in.		±0.020[e]	±0.025[i]	1/64[j]	+0.005 bias[k,l,m]
Shoulder gaps,[b] in.		±0.020[f]			
Bow, in.		±0.020	±0.020	1/64[j]	
Twist		±1/2 degree			
Water Channel,[c] in.		±0.002[g]	±0.002[i]		-3 to -9% bias[k,n,o]
Rod[d] Bow, in.	±0.005 to 0.010		±0.002	0.010 range	+5% bias[k,n]
Rod[d] Length, in.			±0.025[i]		+0.005 bias[k,m]
Rod[d] Profile (Diameter), in.	±0.0002		0.0005[i]		
• Fuel Rod:					
Length, in.		±0.020[e]	±0.015[i]	±0.005	not stated[p]
Profile (Diameter), in.		±0.0002[h]	±0.0002[i]	±0.0005	+0.00011 bias[q]
Axial Location, in.				±0.10	±0.06
Bow, in.				±0.02	

(a) Conversions: 0.0010 in. = 0.025 mm and 0.10 mm = 0.0039 in.
(b) Fuel rod shoulder-to-upper end fitting distance.
(c) Fuel rod-to-fuel rod spacing.
(d) Peripheral rods
(e) For optical measurements of length, the precision is ±0.012 in. and the system bias is up to 0.073 in. due to optical parallax.
(f) For optical measurements of shoulder gaps, the precision is ±0.005 in. and there is no system bias.
(g) For optical measurement of channel closure, the precision is ±10% and the system bias is 0.0065 in. With a commercially available proprietary probe, the precision is ±0.001 in. and the system bias is ≤0.006 in. depending on the channel width.
(h) The precision is ±0.003 in.
(i) Repeatability
(j) Scale with 1/64-in. units
(k) TV capability for typical examination and will vary with lighting and taping quality.
(l) Encoder resolution for this inspection system is 0.001 - 0.0014 in. There is some inspection variability because of the required visual interpretation of the TV-based gaging system. The design goal for length gaging was ±0.025 in. (±0.635 mm) over a 12-ft (3.7-m) length.
(m) Precision (one sigma level) is ±0.009 in.
(n) Precision (one sigma level) is ±7.4%
(o) Actual channel closure is underestimated 3% for small measured values and up to 9% for large measured values of closures.
(p) Precision (one sigma level) is ±0.005 in. nominal.
(q) Precision (one sigma level) is ±0.0004 in.

27, 29, 102, 103) or available. Each fuel vendor probably has at one time or another gaged nuclear fuel for all of these parameters.

Most of the major fuel vendors have a portable special fuel inspection stand or platform that is used to manipulate fuel and provide a stable base for high precision mensuration. Since most spent fuel storage pools were not originally designed for poolside mensuration, this structure is usually set up in the cask loading area, where the interference with fuel bundle movements in the pool is minimized.

One fuel vendor has a semipermanent special fuel inspection platform at one nuclear power station with PWRs where detailed mensural measurements are made. This platform has an independent crane that handles the bundles during the inspection. At other sites, only visual inspection is done. Because the fuel bundles of older designs cannot be easily disassembled, mensural measurements are concentrated on peripheral fuel rods.

Another fuel vendor has a portable small special fuel inspection stand that is attached to a fuel bundle storage position. This stand contains a 360^{o} rotatable CCTV system, which, with the help of the spent fuel handling crane, can scan the total exterior surface of the fuel bundle. More detailed mensuration has been performed with their portable large special fuel inspection stand, which has a periscope, a special probe for measuring fuel rod-to-fuel rod spacing, and linear variable differential transformer (LVDT) gages for fuel bundle and individual fuel rod gaging.

One of the other fuel vendors also uses portable but stable special fuel inspection platforms to make fuel bundle and fuel rod measurements. An emphasis is being made on gaging peripheral fuel rod parameters without bundle disassembly. Rod length, bow [calculated from water channel (fuel rod-to-fuel rod spacing) measurements], and profile have been gaged on single fuel rods in a bundle by moving a hand-held LVDT over a rod. Some experimentation has been done in gaging fuel rod ridging and ovality on peripheral fuel rods while those fuel rods are still in the fuel bundle. The fuel rod is rotated with a driving system and the profilometry head moved axially along the rod. This fuel vendor noted no sign of cladding wear from rod rotation in these tests.

Another fuel vendor has used two special fuel inspection stands or platforms for fuel bundle and fuel rod gaging and two levels of mensural inspection. In the first level, dimensional measurements were made on a fuel bundle using a periscope and background scale comparison gaging. Their special platform for single rod inspection has been used in their second level of mensural gaging, concentrating on single fuel rod mensuration.

Another of the fuel vendors has performed detailed fuel bundle mensuration with their special fuel bundle inspection stand and fuel rod gaging on their special fuel rod inspection stand.

Tables 8.2 and 8.3 summarize the fuel bundle and fuel rod mensuration techniques that have been performed by the major fuel vendors. The mensural techniques range from simple optical comparisons assisted with CCTV and periscope to LVDT and strain gage based probes (e.g., of the proprietary type manufactured by one domestic company), whose readouts can be automatically recorded (Refs. 24, 27, 29, and 102-104). Poolside mensuration is continually evolving, so these techniques do not necessarily represent the current state-of-the-art capabilities.

8.2.2.1 Optical Comparator

An optical comparison gage consists of a viewing aid, such as a periscope or CCTV, and a calibrated scale, which is used as we would use a ruler or tape measure. The dimension to be gaged is visually compared against the scale and the difference determined from vernier markings on the scale or an eyepiece, which has a calibrated cross-hair (bifilar eyepiece) or reticle scale. Another optical comparator approach uses a precision translating table and encoder readout with a cross-hair. The edges of the gaged dimension are sequentially aligned to the cross-hair, and the dimension is read out as the difference in encoder readout for each position. An optical comparator is usually characterized by no physical contact with the gaged part, a lower accuracy than other gaging techniques, and the necessity of a "trained" operator to "read" the dimensions. Optical comparators are limited by the operator's skill and the optical errors produced by the resolution limits and optical distortion from the viewing aid. Scale comparison is also subject to a parallax error whenever

TABLE 8.2. Fuel Bundle Mensuration

Parameter	Data from Fuel Vendors				
A. Fuel Bundle Length	• Visual gage consisting of a periscope and background scales	• CCTV and background scales (using small special fuel inspection stand) • Visual gage consisting of a periscope (bifilar eyepiece) and background scales (using large special fuel inspection stand)	• Dial indicator and fixed gage length (aluminum) using tie plate separation • Visual gage consisting of a periscope (bifilar eyepiece) and background scales		• CCTV with electronic cross-hair and translating platform with encoder position readout
B. Fuel Bundle Bow		• CCTV and background scales • Visual gage consisting of a periscope (bifilar eyepiece) and background scales	• LVDT gage and large anvil channel that contacts upper and lower tie plates and gages the middle grid spacer position	• Visual gage consisting of a periscope (bifilar eyepiece) and background scales	• CCTV with electronic cross-hair and translating platform with encoder position readout
C. Fuel Bundle Twist		• Angle encoded fuel bundle platform and visual alignment with periscope			
D. Fuel Bundle Water Channel	• Special probe (consisting of compressible leaf springs and strain gages) inserted into the bundle	• Special probe	• Special type probe with a leaf spring and strain gage readout and TV monitor to verify insertion action	• Visual gage consisting of a periscope (bifilar eyepiece) and background scales	• Special probe under surveillance with a CCTV system
E. Rod Bow	• LVDT gage translated over a stationary fuel bundle (between fuel spacer grids)	• CCTV in small special fuel inspection stand calibrated with adjacent scales (visual comparison of fuel bundle edge with hanging wire or straight edge)	• Calculated from special probe measurements of water channel dimensions		• CCTV with electronic cross-hair and encoder system to read out dimensions of a translating system
F. Rod Length	• Periscope and background scales	• CCTV (using small special fuel inspection stand) and calibrated scales adjacent to the fuel bundle	• Micrometer and anvil that contacts the two ends of a fuel rod		
G. Fuel Rod Profile	• LVDT gage translated over a fuel rod, between fuel bundle spacer grids		• Hand-held LVDT gage on peripheral fuel rods		

TABLE 8.3. Fuel Rod Mensuration

Parameter	Data from Fuel Vendors			
A. Fuel Rod Length	• Optical gage consisting of a periscope (bifilar eyepiece) and a length standard	• Depth micrometer and anvil (while fuel rod is in the single gamma scan basket)	• LVDT and anvil system calibrated with NBS traceable standard (fuel rod held in a "V" block system)	• LVDT and anvil system with calibrated standard
B. Fuel Rod Profile	• LVDT gage head and calibrated standard (both straight and helical scans) steel rod with diameter and ovality calibration	• Stationary LVDT gaging head (free lateral motion) and calibrated standard	• LVDT gage (straight and helical scans) and calibrated standard	• LVDT gage with axial position readout from the mechanical handler
C. Fuel Rod Bow	• Visually gaged by comparing fuel rod to a straight edge or hanging wire (periscope and background scale readout)		• Periscope and background scale gage on free-hanging fuel rod	

the scale and gaged part do not lie in the same plane. Optical gaging does require careful setup and execution if high accuracy is to be obtained.

8.2.2.2 Linear Variable Differential Transformer (LVDT) Gage

An LVDT sensor is basically a small transformer with two separate, adjacent windings (coils) and a single moveable core. The electronic interface reads the differential impedance between the two coils. With the core midway between the two coils, the gain from each coil is initially adjusted for a null condition. As the core moves between the two coils, this null is upset and a signal is produced that is proportional to the distance moved. Very high accuracy [1.27×10^{-3} mm (50×10^{-6} in.) range] LVDT gages are available. However, the common limiting factor is a range-to-accuracy ratio of 200 to 500 for LVDT gages. LVDT gages are temperature sensitive and usually require frequent calibration to maintain their accuracies. The output signal can, however, be directly recorded without intervention or interpretation by an operator. Contact (indirect or direct) must be made with the points that are to be gaged. Long distances are gaged with an anvil head and the use of a gage length standard. This extends the range of an LVDT gage without an accuracy loss but requires additional calibration of the standard to maintain this accuracy. A lever may also be used to amplify the range of an LVDT but with a corresponding loss in potential gaging accuracy.

8.2.2.3 Probe for Water Channel Measurements

A special probe (e.g., of the proprietary type made by one domestic company) is used to measure fuel rod-to-fuel rod spacing (water channel) in a fuel bundle. Such a probe usually consists of a thin flat member with compressible leaf springs (Figure 8.1); strain gages mounted on the leaf springs read the amount of spring deflection as this flat probe is inserted between fuel rods. Calibration over the total dimensional range of interest is usually required because of the nonlinear response. The gage is normally operated with a set of stepped openings that must be transversed as the probe is extended to enter a fuel bundle. Unlike an optical comparator, this probe will gage fuel rod spacings throughout a bundle wherever there is a clear path through a fuel bundle and not just the peripheral or limiting water channel spacing. To avoid

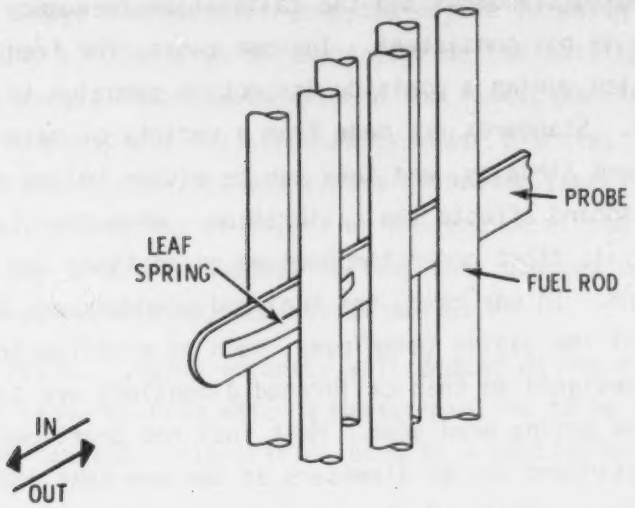


FIGURE 8.1. Example of Probe Used for Measuring Fuel Rod-to-Fuel Rod Spacing (water channel)

fuel damage, the probe's insertion is monitored with a CCTV and load limiting sensors are attached to the mechanical translator. High accuracies are achievable with this probe, although one cannot discern which fuel rod touching the probe has bowed and narrowed the channel. The flat carrier member is made flexible so it can slide between fuel rods without physically damaging the fuel rods.

8.3 Mensural Limitations

In almost all of the mensural inspections, dimensional standards traceable to the National Bureau of Standards (NBS) are used to calibrate gaging hardware. The standards are generally based on visual judgment (bifilar eye piece or enhanced TV raster alignment); the use of a standard that is optically identical to the real fuel rods and bundles is vital. Subtle changes in shadowing and image parallax can produce significant bias errors in the dimensional readout. The color or contrast changes from crud can also affect the optical image and the subsequent ability to reproducibly locate a particular point or surface (e.g., the edge of a fuel rod or a fuel bundle end fixture).

The design of gaging standards and the calibration frequency used in the nuclear industry is not consistent. In some cases, the frequency of calibration is even varied during a poolside inspection campaign to prevent a critical path interaction. Standards are made from a variety of materials, including stainless steel and Zircaloy, and they can be either hollow or solid. The design of the standard affects the calibration. When the standard is made from the proper material, first order temperature corrections are automatically taken into account. In one case, the fuel rod standard was solid and made from Zircaloy. Some of the gaging techniques, such as profilometry and water channel gaging, are designed so that calibrated dimensions are traversed at the extreme end of the gaging head scan. Most fuel rod profilometers have been designed with a standard set of diameters at one end that are gaged when the profile head is moved off the fuel rod, and most of the applications of the special probes (gages) for measuring fuel rod- to-fuel rod spacing (water channel width) have calibrated gaps that are traversed when the probes are fully inserted and withdrawn from the fuel bundles.

Temperature can be a very large problem for gaging, especially if high accuracies are required over long gage lengths. Monitoring the temperature of the pool water is normally sufficient for the less accurate dimensional tasks. With an irradiated fuel bundle that is generating considerable heat, there can be a rather significant difference between the average temperature of the pool water and the temperature of the water in the center of the fuel bundle. This means a delay before mensural inspection tasks can be undertaken. With a normal poolside inspection, the fuel has usually cooled enough so there is very little temperature difference between the pool water and the fuel. At this point, potential thermal errors can be managed with standard pool water temperature measurements. It is very difficult to accurately gage the temperature of such an object when it is immersed in water because of the difficulty in achieving good thermal contact between a thermal sensor and the surface to be measured and because of the heat conduction/ convection of the water.

Mensural techniques that use an optical system are sensitive to the pool water optical conditions and the operation of the viewing aids. Some of the potential limiting factors for visually assisted gaging include the following:

- Image Sharpness: Image sharpness affects the degree to which an observer can overlay a filar with an image edge or the ability to read and estimate partial increments between the finest markings on a scale. Image sharpness will be affected by water clarity, image focus, optical system resolution, and system vibration (specifically for photography). The overlay of filars or projection of features on background scales is a very subjective task that depends on the operator's training, experience, and visual skills.
- Depth of Field: Optical gaging accuracy will depend on the field depth between the features from which a measurement is to be made. The parallax error can add a significant bias to a particular measurement.
- Calibration: The calibration technique should require the same visual judgement as the actual gaging task, such as referencing between rounded rather than sharp edges and referencing the same spatial contrast patterns. If one is gaging across a bright span, a different bias will result than when one is gaging across a dark image span between two bright areas. The "true" location of an image edge is at the 50% intensity point, which is very difficult to locate visually (Ref. 105).
- Image Magnification: The ultimate gaging accuracy will also depend on the optical system magnification. However, the magnified image must also be sharp enough to utilize the full benefit of the system magnification.
- Motion: Some image motion can actually help one define the location of a feature, especially if the viewing aid resolution approaches the desired edge location accuracy. For photography, however, vibration merely degrades an image, depending on the object's velocity and the exposure time for photography. When a short photographic exposure time is desired, very intense illuminating lights are usually required to produce a bright image.

- Fatigue: Fatigue is one of the subjective factors that affects the total visual inspection task. Images that are too bright or dim and viewing aids that strain the eyes enhance the fatigue factors. Viewing aids should be designed with the proper image brightness and overlay of scales or filars with an image to minimize fatigue and potential judgment errors.

Some of the limiting gaging accuracies for visually assisted mensuration are shown in Table 8.4. These data were summarized from discussions at the meetings and from the literature search.

Mensural techniques that use direct transducer readout are subject to contact, alignment, and temperature errors. The thermal coefficient of expansion for Zircaloy tubing is approximately 1.67×10^{-6} mm/mm-K (3×10^{-6} in./in.-^{o}F) for both diametral and axial tube physical dimensions (Ref. 106). For a temperature increment of 2.8K (5^{o}F) in a 12.7-mm (0.5-in.) diameter, 3.81-m (150-in.) long Zircaloy tube, the resulting diametral and axial changes will be approximately 1.91×10^{-4} mm (7.5×10^{-6} in.) and 5.72×10^{-2} mm (2.25×10^{-3} in.), respectively. This indicates that a $\pm$2.8K ($\pm$5^{o}F) temperature measurment error could produce a significant mensural error, especially for long gage lengths. The measurements of the pool water temperature may not be sufficient to characterize the temperatures when gaging, especially within a fuel bundle.

TABLE 8.4. Common Mensural Tools and Their Gaging Accuracies

Mensural Tool	Accuracy
Periscope with bifilar eye piece	$\pm$0.51 mm ($\pm$0.020 in.)
CCTV with enhance roster and encoder position readout	+0.13 mm (+ 0.005 in.) Bias[a]
Rotary table encoder and periscope	$\pm$1/2 degree
Strain gage probe[b]	$\pm$0.051 mm ($\pm$0.002 in.)[c]
Dial indicator/depth micrometer	$\pm$0.64 mm ($\pm$0.025 in.)
Linear voltage differential transformer (LVDT)	$\pm$0.0051 mm ($\pm$0.0002 in.)

(a) Precision (one sigma level) is $\pm$0.023 mm ($\pm$0.0009 in.)
(b) Probe accurracy is $\pm$0.0051 mm ($\pm$0.0002 in.).
(c) Includes analysis of measurements.

In producing highly accurate dimensional measurements, the design and use of gaging hardware becomes important. In diameter and length measurements, squareness of the gaging tips, with respect to the piece to be gaged, can affect dimensional measurements where high accuracy is needed. The measurement task is made more difficult by poor visibility and separation of an operator from the gaging hardware. Some of the more critical gaging tasks require that the gaging head be rocked back and forth to cross the true dimensional gaging position and that signal processing of the transducer output then be used to eliminate these alignment errors. Critical gaging tasks can also be monitored with CCTV systems, which can alert an operator to immediate problems with gaging hardware.

Gaging accuracies for common poolside mensural hardware are shown in Table 8.4. More accurate transducers (LVDT type) are available; however, the operating range is decreased when the accuracy is increased (a rule of thumb for LVDT-type transducers is a range-to-accuracy ratio of 200-500 for common commercial LVDT components).

Electrical noise, moisture, and radiation are additional limiting factors with mensural hardware and measuring procedures. The use of highly accurate optical interferometry techniques is hampered by the radiation levels and the pool water clarity, so most mensuration techniques involve contact gaging with an electronic displacement readout (strain gage or LVDT). Optical noncontact gaging has been effective in similar reactor cladding gaging applications with accuracies in the $\pm 1.02 \times 10^{-3}$ mm ($\pm 40 \times 10^{-6}$ in.) range for diametral gaging (Ref. 107).

8.4 Hot Cell Measurements

This discussion on hot cell measurements is included as a general bench mark. Poolside mensural campaigns are relatively new technologies in comparison with established hot cell technology. Hot cell technology should not be used as the standard for poolside mensuration. In the past, most of the new fuel developments required an extensive mensuration study, much of which was done in hot cells. Poolside mensural measurements are subject to time constraints because of reactor outage considerations; more time is available with

hot cell measurements for the actual mensuration and data reduction. There is a higher gaging accuracy for the hot cell mensuration, as indicated by Table 8.5 (Refs. 34, 36, 38-40, and 108-113).

Today, the differences in gaging accuracy between hot cell and poolside gaging are being rapidly eliminated, as indicated by the typical poolside gaging accuracy data in Table 8.1. Poolside mensuration, which used to be more of a macroscopic analysis tool, is now becoming a microscopic area, similar to today's hot cell technology. Almost all of the tasks that were formerly performed in a hot cell can now be done in the spent fuel storage pool because of the technological evolution in mensuration techniques, equipment, and methods of data inventory. In the past, hot cell tasks led in the development of a particular measurment concept, with poolside applications utilizing the benefits of their technology. Today, hot cell requirements are still producing highly accurate mensural hardware, but the new poolside mensural needs are being met with development directed specifically at poolside inspection problems (Ref. 114). Specific examples are the development of the special water-channel probe and the enhanced raster CCTV/encoder gaging concept. More sophistication in data recording and inventory (with emphasis on automation) is being designed into future poolside inspection hardware. The main objective appears to be the obtaining of highly accurate data with a minimum of manpower and a minimal impact on the reactor refueling outage.

8.5 Unirradiated Fuel

In evaluating poolside mensural inspection data, it should be noted that a detailed dimensional precharacterization of a fuel bundle is an exception rather than a rule. Each fuel bundle is go/no go verified against the overall fuel design tolerance specifications, which are generally considerably larger than the poolside dimensional gaging accuracies. The general rule in a poolside dimensional inspection campaign is to initially pick out several fuel bundles or even individual fuel rods and follow these through several reactor cycles with detailed dimensional inspection. Some fuel bundle measurments, such as bow and fuel rod-to-fuel rod spacing, are meaningful even without a detailed physical precharacterization. Other measurements, such as fuel rod

TABLE 8.5. Hot Cell Measurement

Installation and Company (or Country)	Measurement Parameter	Accuracy and/or Precision		Measurement Method	Calibration
Installation 1	Fuel Rod Diameter	0.00X mm[a] (0.000X in.)		Not described.	None given.
	Fuel Rod Length	0.0254 mm (0.001 in.)		Not described.	None given.
Installation 2	Fuel Rod Diameter		1.02 x 10^{-3} mm (40 x 10^{-6} in.)	Not described.	None given.
Installation 3	Fuel Rod Diameter			Inductive displacement pickup and helical scans.	None given.
Installation 4	Fuel Bundle and Rod:			Not described.	
	Lengths	+0.01 mm (±0.0004 in.)			Length and diameter standards.
	Diameters	±0.005 mm (±0.0002 in.)			
Installation 5	Fuel Rod:				
	Length	0.0254 mm (0.001 in.)		Dial indicator and standard length.	Standard length
	Diameter	0.00762 mm (0.0003 in.)		Not described.	Not described.
Installation 6	Fuel Rod:				
	Length	±1.3 mm (±0.050 in.)		None given.	Step diameter standard, ±0.635 mm (±0.025 in.) differences from the nominal diameter.
	Diameter	5 x 10^{-3} mm (0.0002 in.)	LVDT[b] @ 180°		
Installation 7	Fuel Rod:				
	Diameter	±0.04%		Snap-on dial indicator gage.	Calibrated but no method described.
	Axial Strain	±0.02-0.08%		None given.	None given.
Installation 8	Fuel Rod/Capsule:				
	Diameter	±0.00508 mm (±0.0002 in.)		Dial indicators @ 180°. Pneumatic gage ball slide sensors.	Standard rod with known diameters.
	Length			Lath bed traverse.	
Installation 9	Fuel Bundle:				
	Length	±0.254 mm (±0.010 in.	0.0254 mm (0.001 in.)	Ball screw.	Gaging standard/ dummy bundle.
	Diameter (twist & hex. cross section flat-to-flat also gaged)	±0.0254 mm (±0.001 in.)	(resolution)		
Installation 10	Fuel Rod:				
	Bow		None given.	Direct reading micrometer.	None given.
	Diameter		0.00508 mm (0.0002 in.)	Optical Micrometer, inherent accuracy of 0.0008 mm (0.00003 in.) demonstrated.	Gage blocks.
	Length		±0.00508 mm (±0.0002 in.)	Tapered wedges of micrometer.	Gage blocks.
Installation 11	Fuel Capsule and Rod:				
	Diameter	±0.00254 mm (±0.0001 in.)		Out-of-cell optical gage-image dissector tube.	Standard diameter rods.
	Length	±0.0254 mm (±0.010 in.)		Ball screw.	None given.

(a) Inferred from dimension given, as no exact value given.
(b) Linear variable differential transducer (LVDT).

length and highly accurate fuel rod profilometry, need the specific unirradiated dimensional data to be fully meaningful (any relative type of measurements, such as fuel rod ovality and ridging, do not need the initial fuel dimensional characterization).

8.6 Summary and Conclusions

In comparing poolside mensural inspection techniques and inspection campaigns, several observations can be made. First, there is no standard mensural inspection campaign. In comparing the results from various published inspection campaigns and analyzing the current techniques used by fuel vendors, we found that the effort during each inspection is unique. Some of the mensural data are gathered as a result of an immediate fuel performance problem, while other data are used in fuel code verification. The more established fuel designs appear to have fewer critical mensural requirements than the newer fuel designs or newer fuel codes.

As a rule, utilities do not have an interest in detailed mensural inspection but are interested in failed fuel parameters that may affect the fuel warranty.

Typical time and personnel needs for current poolside mensural inspections of fuel system components are shown in Table 8.6. The trend in poolside inspection hardware is toward automation, which can reduce the amount of manpower required in gathering mensural data (make measurements on assembled fuel bundles rather than on individual fuel rods from disassembled fuel bundles) and reduce the impact on the reactor outage (avoidance of the critical path).

Although there are significant differences in the mensural techniques currently in use by the various fuel vendors doing poolside inspection, most of them have tested almost every measurement concept in their laboratories at one time or another. Mensural techniques and hardware are in a continual state of evolution with a general trend toward higher dimensional accuracies and a lower impact on time and cost at the reactor.

Standards play a very important part in the poolside mensural tasks; however, there is not a uniform approach taken in the design and use of standards. This

TABLE 8.6. Poolside Mensural Inspection Time and Personnel Estimates

Data from Fuel Vendors

Inspection Task	Estimated Time	Estimated Manpower
• Typical poolside inspection		5-6 people
• Bundle length	1/2 day/four sides	
• Water channel[a] measurement	6 hours/bundle	
• Fuel rod bow and diameter (on one bundle face)	2 hours/bundle	
• Optical mensural inspection (no disassembly of fuel bundle)	24 hours/bundle	Two engineers
• Installation and removal of large special fuel inspection stand	2 weeks	
• Probe[b] bundle measurement	12 hours/bundle	
• Bundle bow (hanging and optical gage)	2 hours/bundle	
• Bundle bow (strong back gage)	4 hours/bundle	
• Bundle inspection (with disassembly)	10 days/bundle	
• Fuel rod profilometry	4 hours/rod	
• Detailed inspection campaign		Two engineers and three technicians
• Fuel bundle water channel[a] gaging and visual inspection	12 hours/bundle	
• Inspection of 125 fuel rods from seven fuel bundles	21 days	
• Fuel bundle movement and tie plate removal and replacement	7-9 hours/bundle	
• Channel gaging of a single fuel bundle span between grid spacers	7 minutes/span	
• Inspection platform setup; poolside visual inspection[c]	3-4 days	3-6 people/ 10-12-hour shift
• Typical detailed inspection	10 days	Three engineers and three technicians
• Individual fuel rod inspection (included disassembly and reassembly of fuel bundle)	2-3 hours/bundle	
• Single rod total inspection	3 hours/rod	
• Basic closed-circuit television (CCTV) inspection	1-day equipment setup time	One engineer and one technician/shift
• Video tape 20 fuel bundles; perform water channel gaging on 5 bundles	14 days	

(a) Fuel rod-to-fuel rod spacing.
(b) Using proprietary-type probe manufactured by one domestic company.
(c) Actual time for an inspection depends on the amount of photography required for the located anomalies.

is partially due to the fact that standards generally are designed for an optimum performance with the specific measurement technique, such as the replication of a fuel bundle segment for visually aided dimensional measurement. Today, some standards are being designed to provide an automatic first-order temperature correction, thus reducing the data reduction task.

Because of the uniqueness of poolside inspection campaigns and the wide variation in gaging techniques, it would be very difficult to standardize poolside mensuration. Within their accuracy constraints, no one technique can be justified today as being superior. In the future, however, because of potential fuel damage from handling and tool contact, emphasis should be placed on the development of noncontact gaging techniques that do not require the subjective judgment of an operator.

9. EDDY-CURRENT INSPECTION

9.1 Introductory Comments

9.1.1 Use of Eddy-Current Testing

Nondestructive testing by electromagnetic methods involves inducing electric currents (eddy currents) in a metal test object (specifically Zircaloy fuel rod cladding) and electronically measuring the changes produced when the eddy currents are altered by inhomogenities in the test object. These inhomogenities can be of a physical nature such as a crack, pit, lap, or dimensional variation, or can be a result of process differences such as heat treatment, hardness, and chemical composition. Eddy-current testing is a nondestructive method used to characterize metals containing these inhomogenities. Metals containing unwanted defects can be quickly sorted out, enabling the manufacture of quality products.

In light water reactors (LWRs), Zircaloy-2 and Zircaloy-4 cladding (Zry-2, Zry-4) is used to contain the uranium dioxide (UO_2) fuel pellets in the fuel rod. The fuel cladding acts as a principal barrier against the release of radioactive fission products into the primary coolant system. The cladding also acts as the heat transfer boundary between fuel and primary coolant. Fuel bundle damage and rod failure are possible during normal reactor operation, as well as during abnormal operation (Ref. 115). Eddy-current testing is one nondestructive method used to inspect, detect, characterize, and assess the integrity of nuclear fuel rods.

9.1.2 Measurement Principles

During some refueling outages at reactor sites, fuel rods are examined underwater using the eddy-current inspection technique. An eddy-current inspection probe encircles the fuel rod, positioned in a test fixture as shown in Figure 9.1. The inspection probe, called an encircling coil probe, is composed of many wires wound around a nonconducting disk with a hole in the center into which the fuel rod fits.

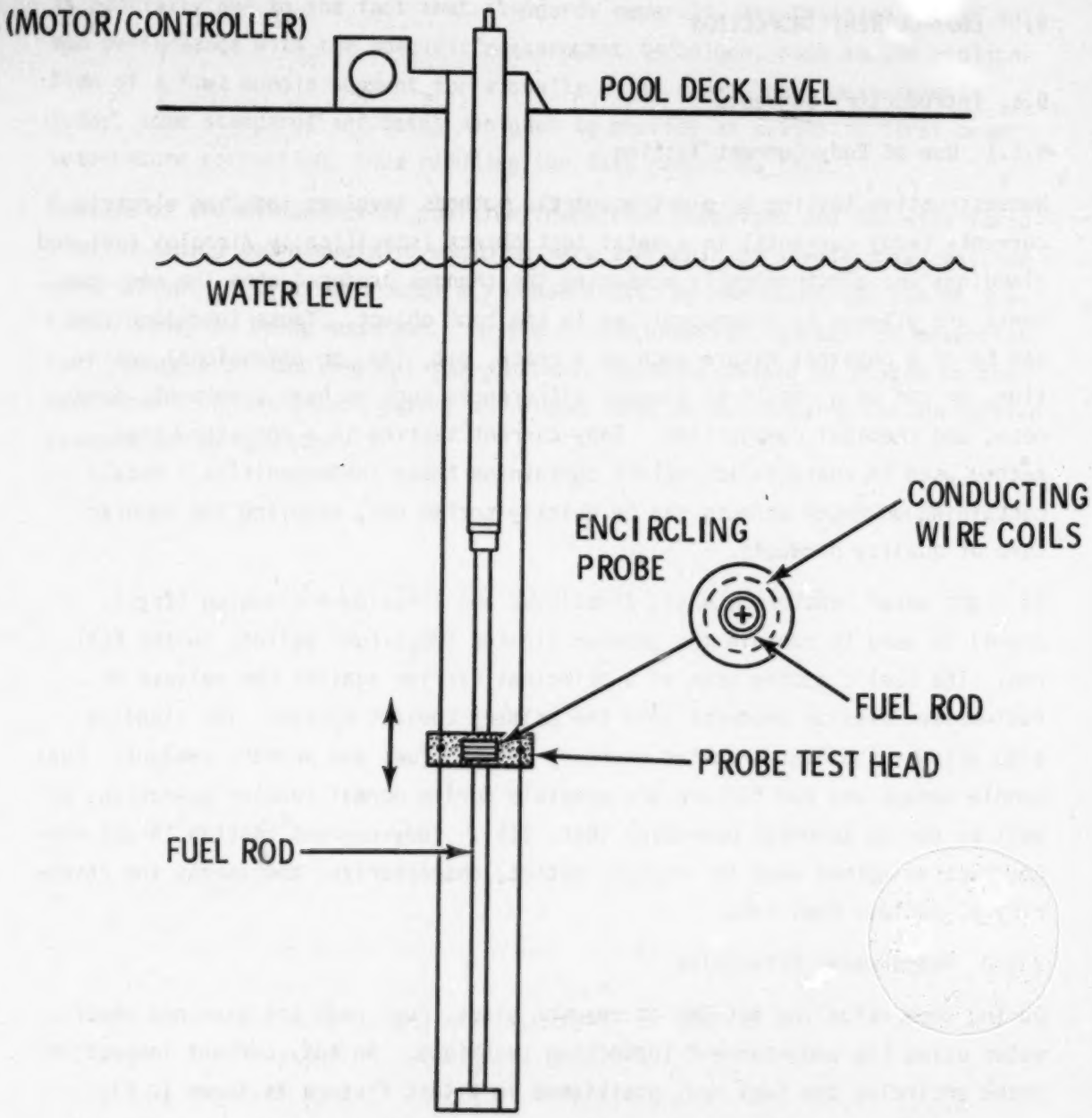


FIGURE 9.1. Eddy-Current Inspection at the Spent Fuel Storage Pool

An eddy-current instrument is used to energize the search coils (i.e., the conducting wire coils in Figure 9.1) of the probe, causing a magnetic field coupling to exist between the search coils and Zircaloy fuel rod cladding. The alternating magnetic field induces eddy currents to flow circumferentially around the cladding wall. The eddy currents in turn induce a secondary voltage in the search coils that can be used to interpret cladding parameters. If defects are present in the cladding, this will cause a perturbation in the normal flow of eddy currents in the cladding, resulting in a change in the induced voltage in the search coils. The defect signal is detected and processed electronically and is typically displayed on a strip chart recorder.

Skilled inspection personnel interpret the eddy-current inspection data and, from their analysis, classify each fuel rod according to its defect condition.

9.2 Electromagnetic Properties of Metals

One of the important electrical properties of metals is conductivity. Simply stated, the conductivity of a metal is a measure of the ease of electron flow within a metal. Mathematically, conductivity can be expressed as the reciprocal of the metal electrical resistivity:

$$\sigma = \frac{1}{\rho} \tag{1}$$

where σ = conductivity (mho/unit length); ρ = resistivity (ohm/unit length).

The conductivity of metals varies widely and depends on parameters such as alloy composition, crystal structure, and impurities. Metals such as copper and silver have high electrical conductivity and are referred to as conductors because of their ability to conduct electric current (electron flow). Materials such as rubber are nonconductors or insulators and will not conduct electric currents. Hence, eddy currents cannot be established in nonconductive materials.

All materials contain inhomogenities. The inhomogenities in metal conductors make it more difficult for electrons to flow in the metal, thus decreasing the electrical conductivity. The presence of large inhomogenities, (e.g., cracks) changes the eddy-current flow or distribution in a metal test specimen. It is this change in conductivity, caused by the presence of the crack in the metal, that can be measured directly using eddy-current testing techniques.

In electromagnetic testing, the permeability of a metal is an important property. Permeability is defined as the ability of a material to permit the setting up of magnetic lines of flux (force field). As in the case of electrical conductivity, the permeability (magnetic response) of metals varies considerably. Metals are classified as being magnetic or nonmagnetic. Materials having a permeability slightly greater than that of a vacuum (which is essentially unaffected by a magnetic force field) are called paramagnetic materials; materials having permeability values less than that of a vacuum simply do not respond to magnetic force fields and are called diamagnetic materials. Materials that are dramatically affected by the presence of a magnetic force field are called ferromagnetic materials (e.g., iron and nickel) and exhibit very high permeability values. Paramagnetic and diamagnetic materials are often referred to as nonferromagnetic materials. Zircaloy cladding is a nonferromagnetic material.

9.3 Electromagnetic Properties of Search Coils

One method of producing eddy currents in a test specimen (fuel rod) is to make the specimen the core of an air induction coil as shown in Figure 9.2. The coil is energized using an alternating current source. The current flowing in the coil establishes a magnetic force field (lines of flux) about the coil. At the same time, the coil magnetic field induces eddy currents to flow in the test specimen as shown in Figure 9.3. The eddy currents in the test specimen flow in the opposite direction to the current flow in the coil windings. The eddy currents in turn set up their own magnetic field in opposition to the original magnetic field of the coil.

When defects are encountered in the test specimen, the flow of eddy currents in the cladding is altered, as shown in Figure 9.4. This causes the impedance

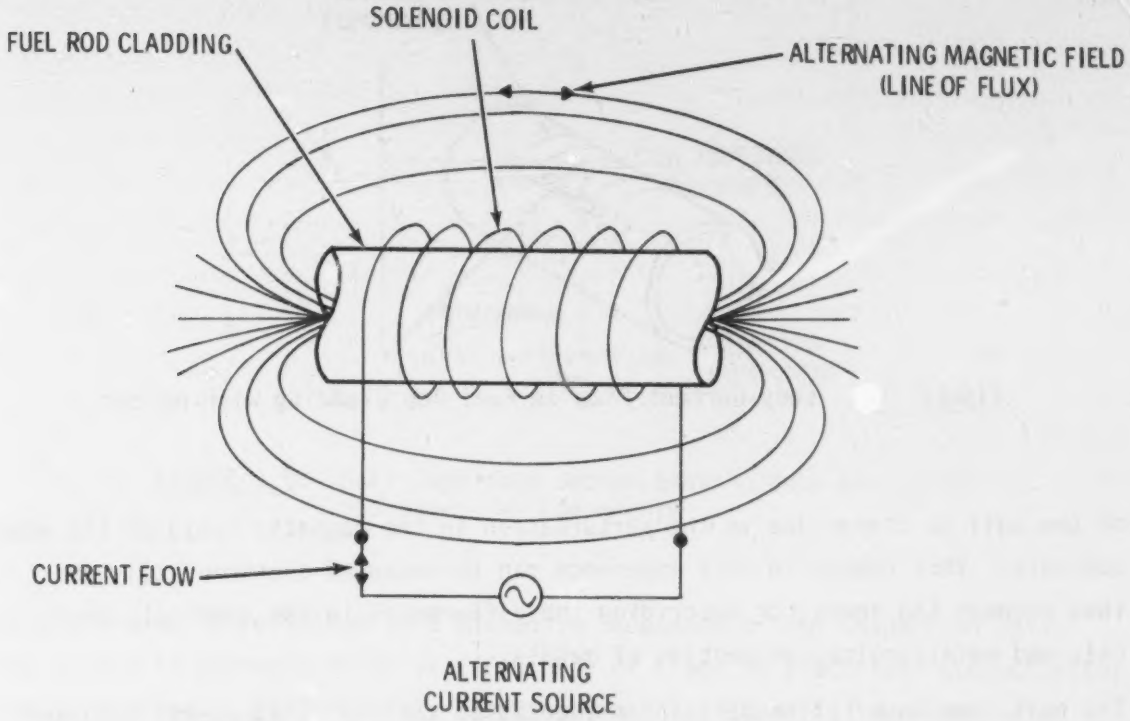


FIGURE 9.2. Solenoid Coil Encircling Fuel Rod Showing Alternating Magnetic Field

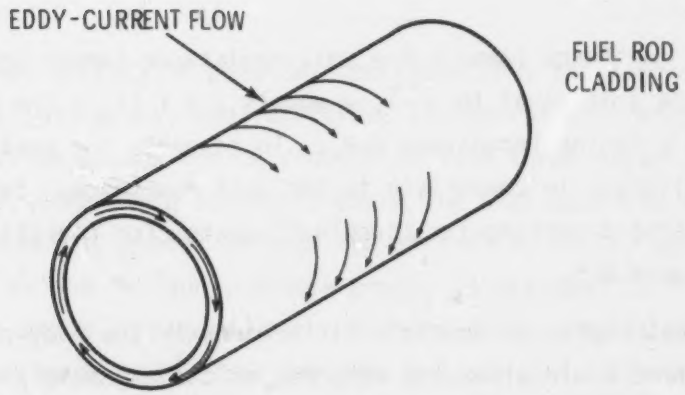


FIGURE 9.3. Eddy-Current Flow In Fuel Rod Cladding

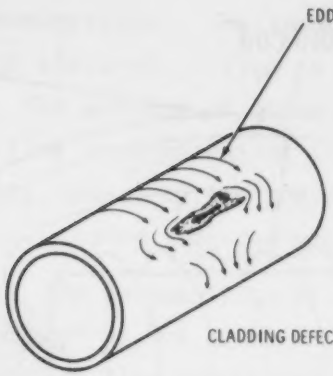


FIGURE 9.4. Eddy-Current Flow in Fuel Rod Cladding With Defect

of the coil to change due to the perturbation in the magnetic field of the eddy currents. This change in coil impedance can be measured electronically and thus becomes the means for describing the differences in the chemical, physical, and metallurgical properties of metals.

The coil impedance (Z) is defined as the sum of the real (resistive) component of impedance and the reactive (in eddy-current testing, the inductive) component of impedance. Mathematically, the impedance of the coil is defined as:

$$Z = R + jwL \qquad (2)$$

where Z = coil impedance (ohms); R = coil resistance (ohms) and jwL = coil reactance, where j is equal to $\sqrt{-1}$, w equals 2 π f [f is the test (excitation) frequency] and L is the inductance (μH). In general, the coil resistance is considered negligible in comparison to the coil reactance. Impedance vectors can be drawn using a rectangular coordinate system for clarification of terms as shown in Figure 9.5.

There are a great number of possible differences in the eddy-current system and test material that could alter the response of the magnetic field produced by the circulating eddy currents. The alternating magnetic field of the inspection coil is affected by changes in the magnitude, phase, and distribution of the induced eddy currents in the test specimen. Any change in the flow of

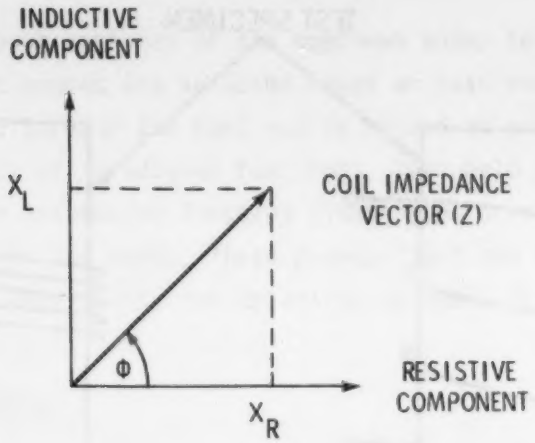
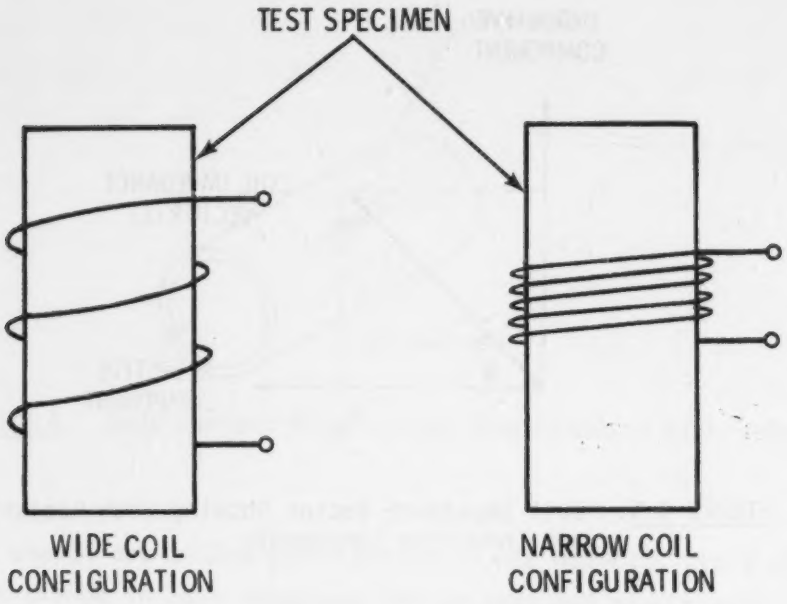


FIGURE 9.5. Coil Impedance Vector Showing Both Resistive and Inductive Components

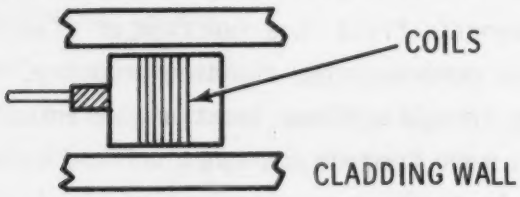
eddy currents is reflected in a change in impedance of the inspection coil. The change in magnetic field is a function of cladding electrical conductivity; cladding magnetic permeability; cladding geometry; cladding inner and outer diameter surface irregularities; location, orientation, and types of defects in the cladding; test frequency; magnetic field strength or magnetizing force; encircling coil-to-cladding spacing (called the fill factor[a] of the coil); and encircling coil size and shape (number and diameter of turns, length, and diameter of windings).

Because of the great variety of physical configurations that require testing using eddy-current techniques, many different inspection coil probes have been developed. Inspection probes can be classified into three major categories. The first category, encircling coils, is where the test specimen (e.g., solid bar or thin wall tube) is passed through the encircling coils, as shown in Figure 9.6a. The second category, bobbin probe, is designed to fit inside a tubular product as shown in Figure 9.6b. The third category is the point probe, which can be hand held. This provides greater versatility for

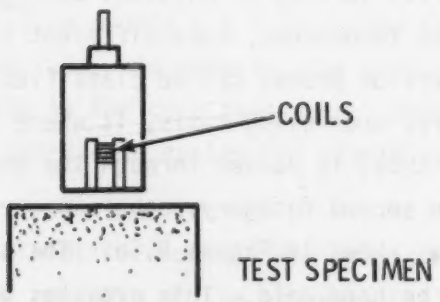
(a) The fill factor is defined as the ratio of the square of the diameter of the fuel rod to the square of the average diameter of the encircling coil.



(a) ENCIRCLING COIL PROBE



(b) BOBBIN PROBE



(c) POINT PROBE

FIGURE 9.6. Eddy-Current Probes

inspectors to move about surfaces of the specimen under test, as shown in Figure 9.6c. Inspection probes are selected based on test requirements. Bobbin probes cannot be used because the fuel rod is welded at each end. Because of the high radioactivity of irradiated fuel rods, hand-held inspection probes cannot be used. When inspecting Zircaloy cladding on irradiated fuel rods, narrow encircling coils are used. These probes limit the eddy-current test area, increasing the sensitivity for detection of small flaws and diameter variations.

9.4 Eddy-Current Theory

Eddy current testing is based on the principle that an electric current (i.e., the eddy current, which is also known as a Foucault current) is induced within the body of a conductor (Zircaloy cladding) when the conductor is moved through a nonuniform (alternating) magnetic field or is located in a region where there is a magnetic flux change (Ref. 116).

The reader should note that further discussion is limited to the case where permeability of materials is constant. Recall that Zircaloy fuel rod cladding is a nonferromagnetic metal (diamagnetic). Therefore, changes in the Zircaloy conductivity are of interest.

The induced eddy currents in the fuel rod cladding tend to be concentrated at the surface of the cladding as shown in Figure 9.7. This phenomena is known as the "skin effect" (Ref. 85). If the conductivity of the cladding is assumed constant, then the depth of penetration of eddy currents can be calculated using equation (3):

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \qquad (3)$$

where δ = depth of current penetration, f = test frequency (Hertz), σ = electrical conductivity (mho/meter), μ = magnetic permeability (for nonmagnetic metals such as Zircaloy, μ equals $4\pi \cdot 10^{-7}$ Henry/meter).

One standard depth of penetration (δ) is defined as being equal to the depth at which the magnitude of eddy currents are equal to 37% of the magnitude of currents at the surface of the cladding. In testing of Zircaloy-clad fuel

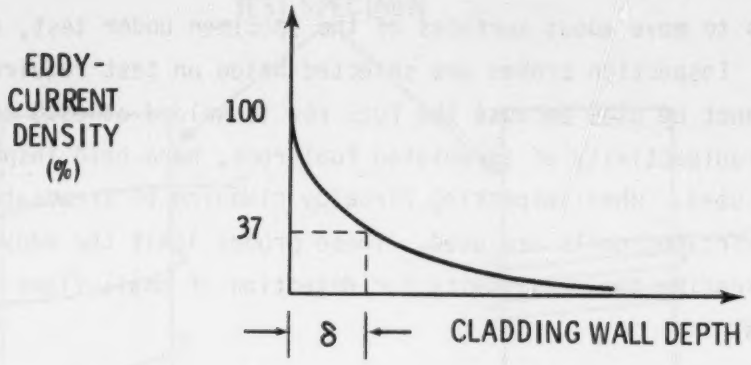


FIGURE 9.7. Eddy-Current Skin Effect

rods, it is assumed that the conductivity and magnetic permeability are constant; therefore, the depth of penetration depends solely on the selected test frequency. A given test frequency can be chosen to achieve the desired depth of penetration. For example, BWR fuel rod cladding wall thickness is typically 0.84 mm (0.033 in.) while PWR fuel rod cladding wall thickness is 0.61 mm (0.024 in.). For Zircaloy-2, one standard depth of penetration equal to the wall thickness of BWR and PWR cladding requires test frequencies of 250 kHz and 500 kHz, respectively. At a test frequency of 1000 kHz, one standard depth of penetration is 0.42 mm (0.016 in.). Thus, higher test frequencies concentrate the density of currents near the surface of the specimen under test.

The depth of penetration of eddy currents in the Zircaloy cladding was shown to be a function of test frequency. The radial and axial distribution of eddy currents in the cladding depends on the test frequency and inspection probe size and configuration. Narrow encircling coils are used to inspect fuel rod cladding. The magnitude of eddy currents is greatest for the cladding section within the immediate core of the coil. The current density decreases as one moves further away from the search coils because of the decreasing magnetic field strength at the coil extremeties as shown in Figure 9.8.

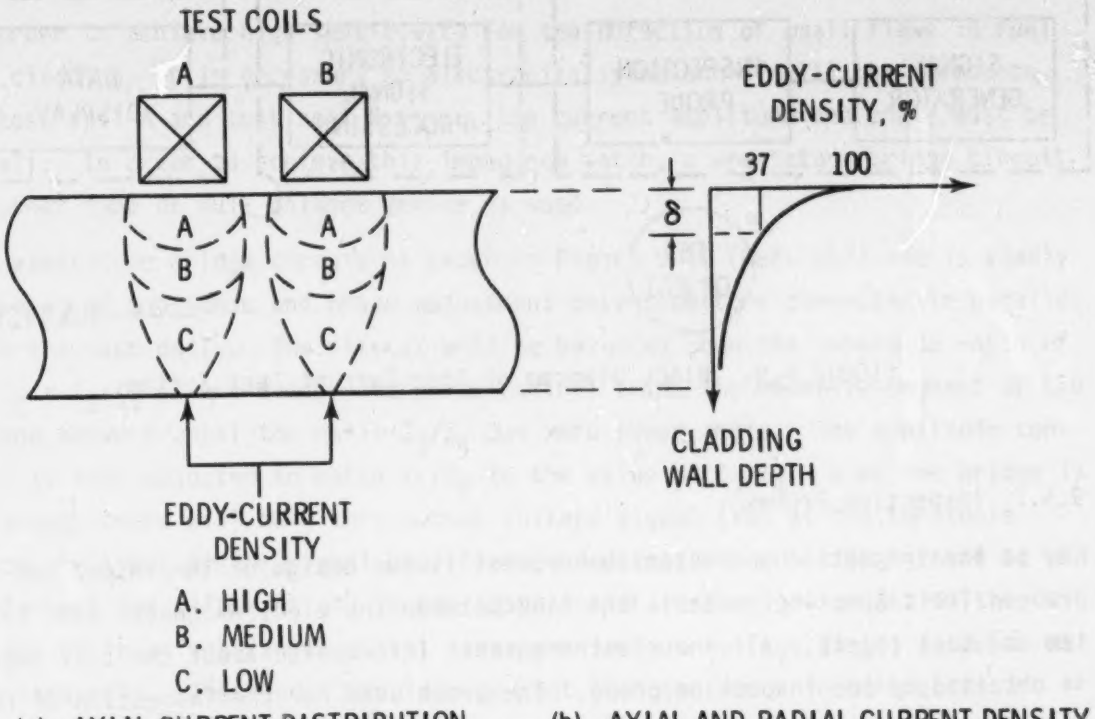


FIGURE 9.8. Eddy-Current Distribution In Fuel Cladding

9.5 Eddy-Current Test System

Eddy-current test systems vary in complexity. They can be simple or complex, and depend on inspection requirements. However, whether simple or complex, eddy-current test systems must be capable of providing three major functions. These functions include: 1) the generation and detection of eddy currents, 2) electronic processing of the detected eddy-current signal information, and 3) recording and display of the eddy-current data in a usable form. The eddy-current test system is composed of three subsystems as shown in the block diagram in Figure 9.9. Test systems used for inspection of Zircaloy cladding of fuel rods are similar in design and operation. The major subsystems of an eddy-current test system will be discussed below.

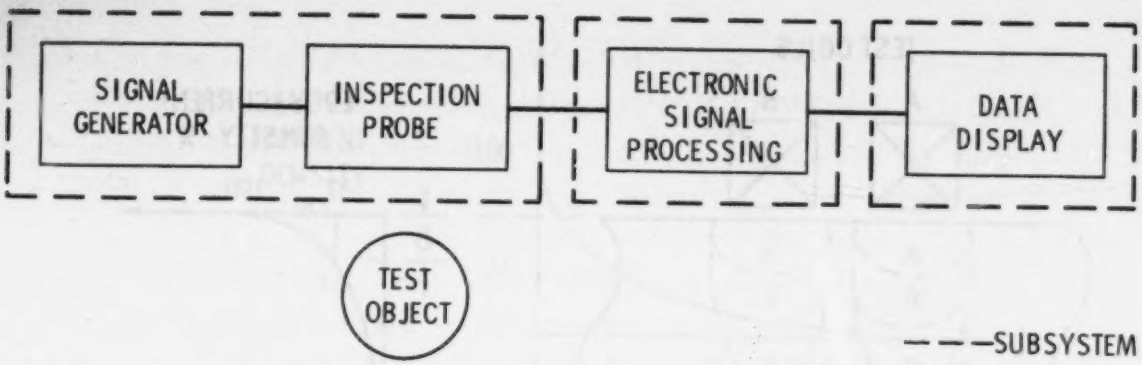


FIGURE 9.9. Block Diagram of Eddy-Current Test System

9.5.1 Inspection Probes

Key to the inspection and detection process is the design of the inspection probe. The inspection probe is the link between the electromagnetic test system and test object. All the electromagnetic information about the test object is obtained by the inspection probe. The probe used for the inspection of fuel rod cladding is called a differentially wound encircling coil probe and is shown in Figure 9.10. Two coils (test coil A and B) are connected in series and are wound around an open core nonconducting material. The narrow coils are closely spaced. Insertion of a fuel rod into the open core of the differential encircling coil will cause a change (modulation) in the magnetic field of the coils.

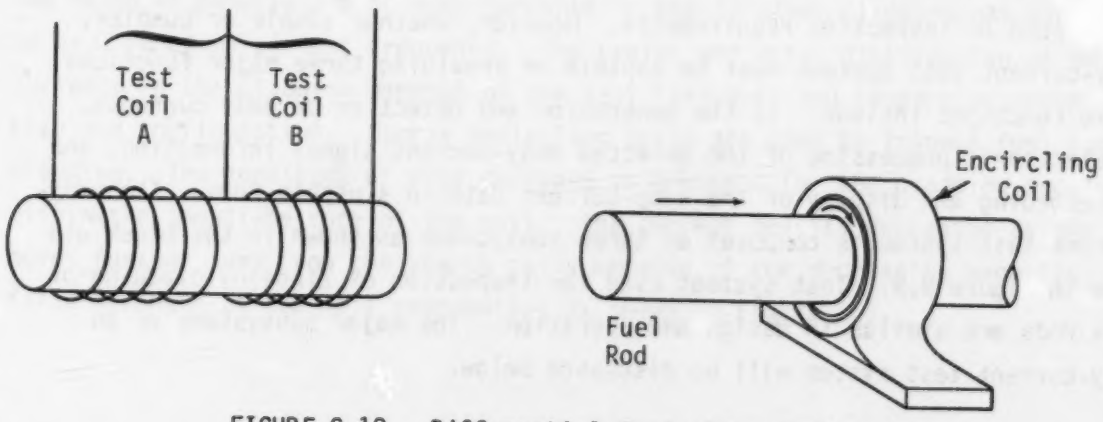


FIGURE 9.10. Differential Encircling Coil Probe

In order to achieve high sensitivity for the detection of small flaws in fuel rod cladding, it is necessary to electronically balance (null) the impedance of test coil A and test coil B (i.e., the current amplitude and phase must be equal). In order to achieve this impedance match, a wheatstone bridge circuit or other type of null balance device is used.

The wheatstone bridge circuit is shown in Figure 9.11 (Ref. 117) and is simply composed of amplitude and phase adjustment potentiometers connected in parallel with the test coils. The circuit will be balanced when the impedance ratio of $Z_1/Z_2 = Z_3/Z_4$ is achieved. The phase control trims the reactive segment of the bridge network until the ratio Z_3/Z_4 has zero phase angle. The amplitude control is then adjusted to match Z_1/Z_2 to the value of Z_3/Z_4. When the bridge is balanced, there will be a zero output voltage signal (Vo) at the terminals which are input to the signal amplifiers and detectors. Only when there is a difference (or differential) in the impedance of test coil A or B will the bridge be in an unbalanced state, causing an output voltage signal to occur at the terminals. The reader should note that changes common to both coils or gradual changes in the electrical (or magnetic) properties of the cladding may not produce a detectable signal.

There are advantages and disadvantages when using encircling coil probes. The advantages are: a) the ability to inspect the entire circumference of the

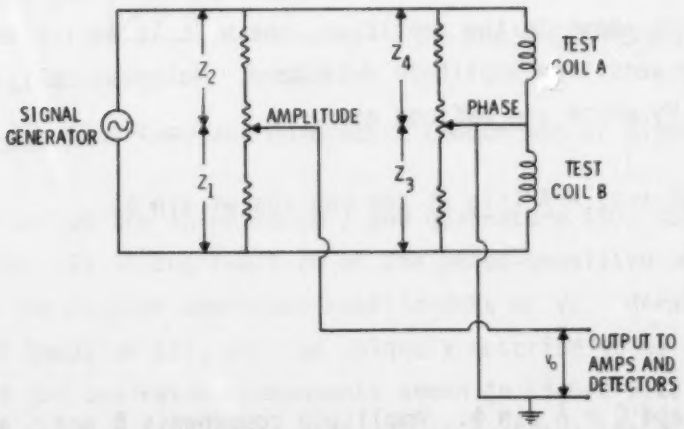


FIGURE 9.11. Eddy-Current System Wheatstone Bridge Circuit (Ref. 117)

cladding (100% volumetric inspection), b) probe geometry lends itself to high speed inspection of tubular shaped products, c) probes can be constructed to have good durability, d) probes are generally small and compact, and e) probes are not affected by high radiation exposure levels. Some disadvantages are: a) the inability to detect small defects (e.g., incipient cracks) due to the particular characteristics and/or orientation of these defects; b) inability to locate the circumferential position of a defect on the cladding (thus, to pinpoint a defect, a surface point probe having a small localized magnetic field, would be required); and c) the response to changes in conductivity, permeability, fill factor, and dimensional variations (e.g., diametrical shrinkage or ridging). The system response to variables that are not of interest may be greater than the response produced by the variable of interest. Specifically, the signal response due to cladding ridging (bambooing) may produce a stronger eddy-current signal indication than a small incipient crack.

9.5.2 Signal Processing

Basically, the signal processing system is composed of an amplifier, phase-sensitive amplitude detectors, and a phase rotator as shown in Figure 9.12. The encircling coil output signal Vo is defined as:

$$Vo = A \sin (wt + \phi) \tag{4}$$

where A = amplitude, $wt = 2\pi ft$, f = test frequency, t = time, and ϕ = signal phase. Signal Vo is input to the amplifier, where it is amplified and then input to the phase-sensitive amplitude detectors. Mathematically, Vo has components Vx and Vy which are defined as:

$$Vo = A \sin (wt + \phi) = A (\sin wt \cos \phi + \cos wt \sin \phi) \tag{5}$$

$$Vx = B \sin wt \tag{6}$$

$$Vy = C \cos wt \tag{7}$$

$$Vo = Vx + Vy \tag{8}$$

where $B = A \cos \phi$ and $C = A \sin \phi$. Amplitude components B and C are called the Fourier amplitude coefficients of Vo. The components Vx (resistive) and Vy

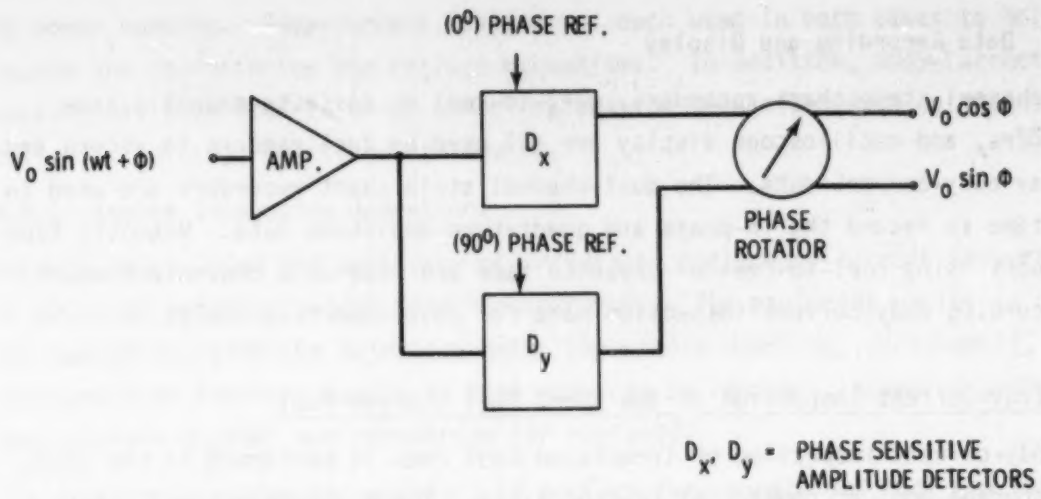


FIGURE 9.12. Eddy-Current Signal Processing Subsystem

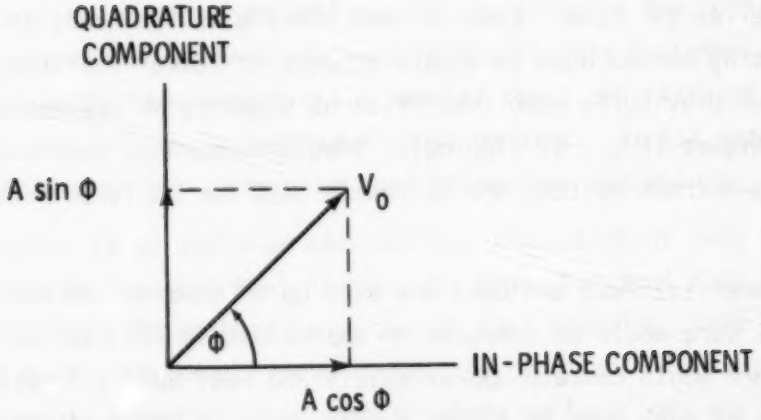


FIGURE 9.13. In-Phase and Quadrature Components of Signal Vector Vo

(reactive) are called the in-phase (0^o) and quadrature (90^o out of phase) components of Vo. It is the function of the phase-sensitive amplitude detectors to detect the Fourier amplitude coefficients of Vo. Because of the linear relationship of Equation (8), one can uniquely describe Vo as a vector in terms of its in-phase and quadrature components shown in Figure 9.13. The phase rotator shown in Figure 9.12 is used to adjust (rotate) the detector output signals in order to properly display the information on the readout equipment.

9.5.3 Data Recording and Display

Dual-channel strip chart recorders, reel-to-reel or cassette magnetic tape recorders, and oscilloscope display are all used by fuel vendors to record and display eddy-current data. The dual-channel strip chart recorders are used in real time to record the in-phase and quadrature amplitude data. Magnetic tape recorders using reel-to-reel or cassette tape are used as a convenient means of recording eddy-current inspection data for postinspection analysis.

9.6 Eddy-Current Inspection at the Spent Fuel Storage Pool

The eddy-current inspection of irradiated fuel rods is performed in the spent fuel storage pool at commercial reactor sites. There are regulatory limits governing the level of radioactive contamination for the reactor coolant system. In order to keep the reactor coolant levels as low as reasonably possible, leaker fuel rods (fuel rods with breached cladding) must be located and removed from the reactor core. Eddy-current testing of fuel rods is one nondestructive testing method used to locate suspect or leaker fuel rods in fuel bundles that have previously been identified as suspects or leakers by other inspection techniques (e.g., by sipping). Single-frequency, continuous wave excitation, eddy-current systems are currently used for poolside fuel rod inspection.

The cores of commercial PWRs and BWRs are made up of hundreds of fuel bundles. Typically, a BWR core would be composed of approximately 700 fuel bundles whereas a PWR core would contain approximately 200 fuel bundles. Because of the large number of fuel rods in a fuel bundle (e.g., a PWR bundle with up to a 17 x 17 rod array or a BWR bundle with up to an 8 x 8 rod array), a rapid, reliable, and sensitive testing technique is needed to inspect fuel rods to assure their leak-tight integrity. Eddy-current testing lends itself to the requirements of inspection speed, reliability, and detection sensitivity.

Fortunately from the inspection standpoint, past water reactor performance data have indicated very low (<1%) fuel failure rates (Ref. 15 and 118). Two major causes of fuel failure have been internal hydriding of the cladding due to moisture in fuel, and pellet-cladding interaction (PCI), thought to be caused

by power ramping. Eddy-current testing has been used in both cases to help locate and characterize the failure mechanisms. In addition, eddy-current testing has been used to study other degradation mechanisms such as cladding collapse, bulging, fretting, and bowing.

9.6.1 Remote Inspection Operations

Because of the high radioactivity of irradiated fuel, eddy-current inspection at poolside requires remote handling equipment. The equipment varies in design and operation, with the objective being the remote handling, disassembly, and reassembly of the fuel bundle so fuel rods can be removed, inspected by the eddy-current system, and reinserted (or replaced).

The electronic equipment necessary to perform fuel bundle and fuel rod inspection is located adjacent to the spent fuel pool where the test personnel can visually observe the handling, positioning, and inspection operations. A crane is used to transport fuel bundles in the storage pool. The crane is located above the pool on a roller assembly so it can traverse the complete length of the pool. Underwater cameras are used to assist test personnel in the fuel handling and inspection operations. Special tools and fixtures are used to disassemble and reassemble individual fuel bundles. Strict operating procedures are followed when performing fuel inspection operations.

There currently is no poolside eddy-current inspection of fuel rods unless the rods are removed from the fuel bundle. In order for fuel rods to be tested using eddy-current inspection, a series of fuel handling, leak test (sipping test), and bundle disassembly operations are required. Fuel bundles suspected of having one or more fuel rods with cladding perforations are first tested for their leak tightness using fuel sipping techniques (see Section 7). Bundles having a high probability of containing failed fuel rods are designated for disassembly so the fuel rods can undergo additional nondestructive examination. For domestic PWR fuel bundles, disassembly typically involves removal of the upper end fixture, except in those cases where the bundle is equipped with an upper end fixture that permits a limited number of fuel rods to be readily removed. For domestic BWR fuel bundles, disassembly first involves removal of the fuel channel (dechanneling), followed by the removal of the upper tie

plate. Fuel rods are typically removed with a special grapple collet tool. Upon removal, each rod is carefully moved from the bundle disassembly station to the nondestructive inspection test station. The grappled fuel rod is moved at a slow rate that enables the fuel rod to maintain a vertical orientation.

Prior to nondestructive testing, the operator may require that the fuel rods be cleaned. If there is a large amount of crud on the rod, an attempt to clean the rod is made. A set of rotating brushes is used to clean the rods. After cleaning, the fuel rod is positioned and aligned in the inspection test station.

9.6.2 Poolside Eddy-Current Inspection

In order to perform the eddy-current inspection, the fuel rod must be either translated past the encircling coil probe (i.e., probe fixed) or the probe must be moved past the fuel rod. Figure 9.14 shows the inspection station of a European vendor with a slide carriage assembly used to translate the encircling

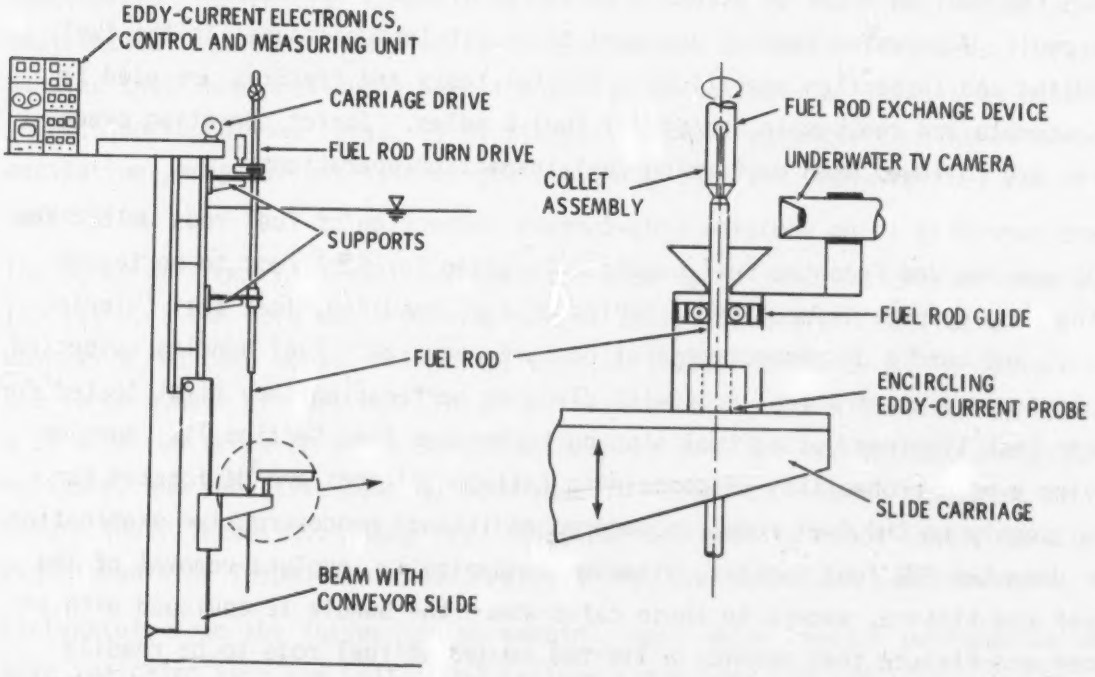


FIGURE 9.14. Example of Eddy-Current Inspection Station at Poolside (Ref. 99)

coil probe along the fuel rod. Domestic fuel vendors use similar systems where the inspection probes are held in a fixture that traverses the fuel rod.

9.6.3 Supplemental Inspection Techniques at Poolside

Eddy-current testing is used for the total (100%) volumetric examination of the fuel rod cladding. However, the eddy-current technique is sensitive to changes in a number of parameters including a) cladding inner and outer diameter surface roughness; b) permeability changes that can result from oxide crud deposits on the clad OD; c) small physical anomalies (0.025 mm or 0.001 in.) such as indentations that may be characteristic of the manufacturing process; d) small fretting wear about the spacer grid, which may not be cause for fuel rod rejection; e) cladding ridging (bambooing), a result of irradiation; and f) surface scratching, possibly produced from disassembly and reassembly of the fuel bundle rod matrix. This list serves to show that the interpretation and evaluation of eddy-current signal information can be a challenging task. An example of eddy-current inspection data from an irradiated fuel rod is shown in Figure 9.15. Note the strong amplitude signals at the spacer grid area. Also shown is an area that is suspected of containing a defect anomaly.

To help discriminate among some of these influencing variables, supplemental nondestructive examination techniques are used. The more common techniques employed are: a) fuel rod profilometry, b) visual inspection, and c) ultrasonic inspection. Profilometry measures fuel rod diameter changes, such as cladding ridging, using linear variable differential transducers. Thus diameter changes indicated by the profilometer system should correlate with eddy-current results for cladding ridging (Figure 9.15). An example of profilometry data is shown in Figure 9.16.

Visual inspection of irradiated fuel is performed using precision borescope, periscope, and television equipment, and is a simple method for assessing the cladding surface condition. Visual inspection of fuel rods is used to confirm: a) the presence of crud deposits; b) fretting wear in the spacer grid area; c) hydride blistering; d) surface scratching; e) OD defects; and f) severe ridging, bowing, or other diameter changes. Another important use of visual inspection is in the examination of the fuel rod end cap weld areas.

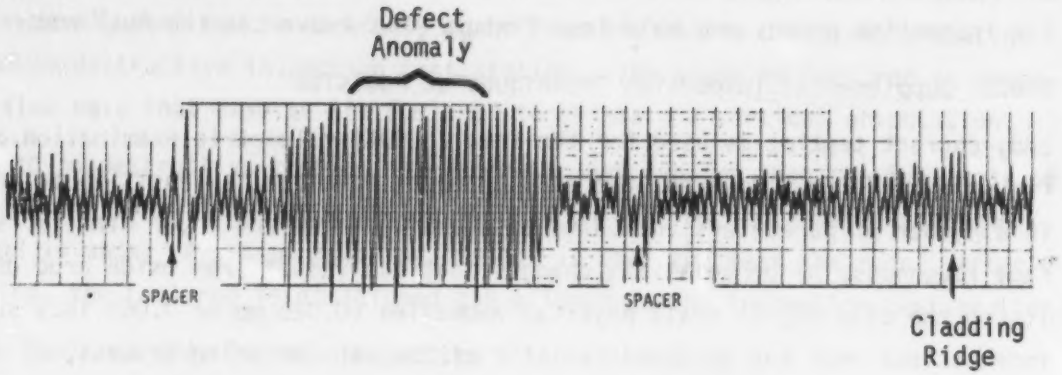


FIGURE 9.15. Eddy-Current Poolside Inspection Data From An Irradiated Fuel Rod

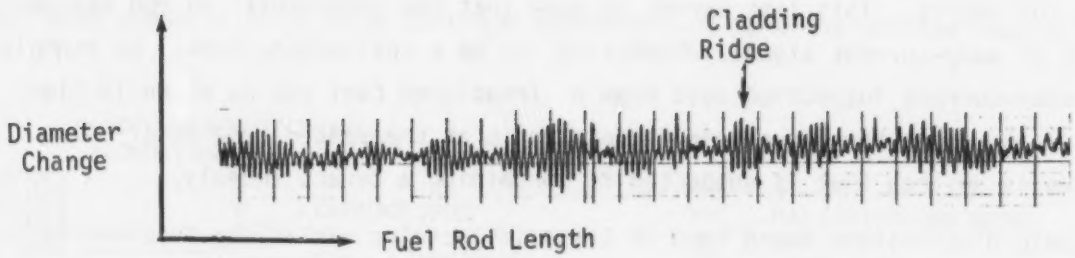


FIGURE 9.16. Typical Fuel Rod Profilometry Scan

Eddy-current inspection is precluded in this area because of the large signal indication resulting from the coil field interaction with the edge of the fuel rod (edge effect).

9.6.4 Eddy-Current Test Standards

Test standards are required in order to establish test system operation and sensitivity. Test standards used at poolside are made using representative fuel rod cladding with artificial defects machined into the cladding.

The standard is developed with the intent to contain known artificial defects that produce eddy-current signals that are indicative of real defect signals. Recall that it is not the defect itself that is detected by the eddy-current

system, but it is the effect of the presence of the defect in the cladding that causes a local change in the electromagnetic properties of the cladding. The use of artificial defects such as electric discharge machined (EDM) slots and/or flat-bottom drilled holes is a common technique employed to simulate defects.

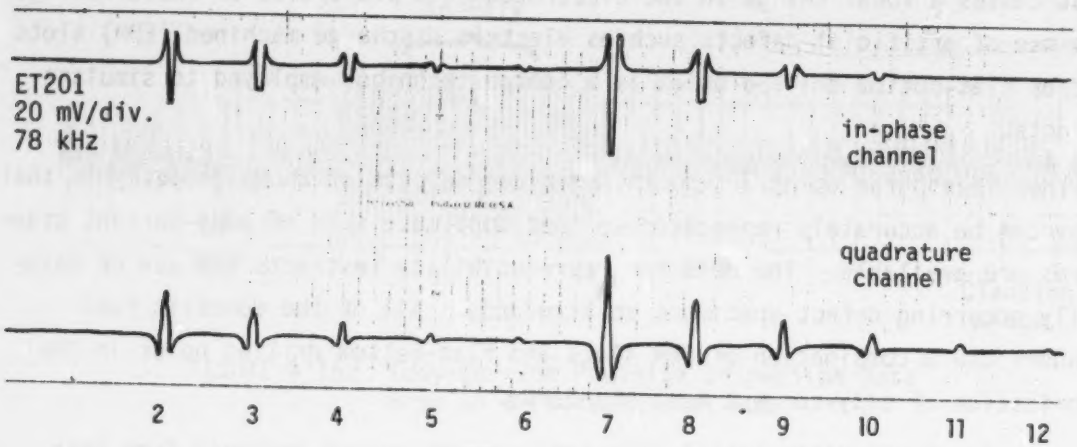
Another reason for using artificial machined defects of known geometry is that they can be accurately reproduced so that duplicate sets of eddy-current standards are available. The need for reproducibility restricts the use of naturally occurring defect specimens as standards. All of the domestic fuel vendors use a combination of EDM slots and flat-bottom drilled holes in the fabrication of eddy-current test standards.

An example of the differential coil eddy-current output response from test standards containing axial and circumferential EDM slots is shown in Figures 9.17 and 9.18 (Ref. 119). The figures show the in-phase (horizontal) and quadrature (vertical) channel outputs from a two-channel recorder. Also shown in Figure 9.18, is the response from a 0.254-mm (0.010-in.) diameter through-wall hole (defect No. 1). The fuel rod cladding wall thickness was 0.381 mm (0.015 in.) and the inspection frequency was 78 kHz. The recorder sensitivity was increased by a factor of 10 to 2 mV/division for recording of the circumferential slot data of Figure 9.18.

9.6.5 Eddy-Current System Calibration

The nondestructive test procedure includes instructions and a standard to be used for calibration of the system. The test standard is used at the beginning of an inspection to establish initial system sensitivity. Final system adjustments are performed after scanning the test standard to establish the desired amplitude response from each defect in the standard.

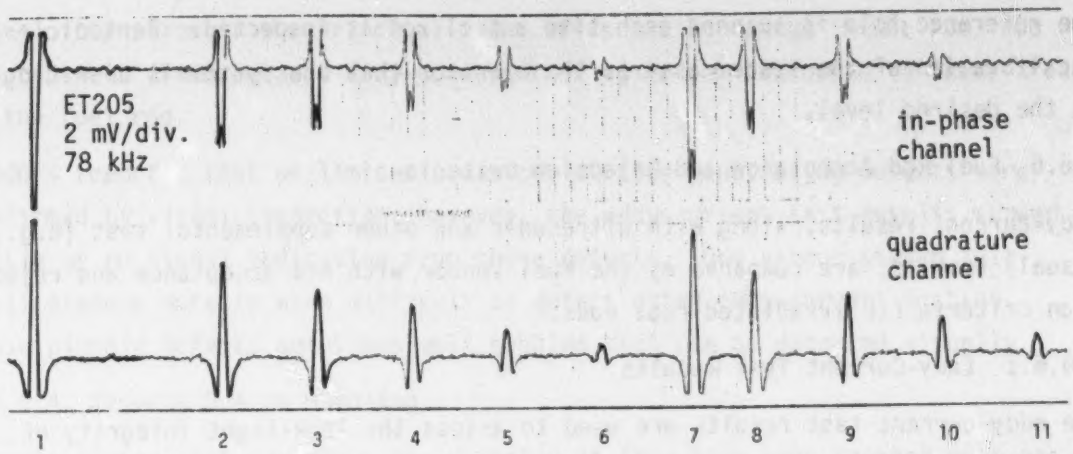
Test procedures require occasional recalibration of the test system as a check on system performance. For example, one fuel vendor required that the test system be calibrated at least every four hours, or, as a minimum after inspecting a certain number of fuel rods, whichever came first. Another vendor uses a through-wall drilled hole standard mounted on the inspection station. Thus



DEFECT NO.	TYPE	LOCATION	DEPTH[a] (% of WALL)
2	EDM[b]	OD	80
3	"	"	60
4	"	"	40
5	"	"	20
6	"	"	10
7	"	"	100
8	"	ID	80
9	"	"	60
10	"	"	40
11	"	"	20
12	"	"	10

(a) Tube wall thickness = 0.381 mm (0.015 in.)
(b) Electric discharge machined (EDM) defect

FIGURE 9.17. Typical Strip Chart Recording of Differentiated Eddy-Current Output (Test Standard - Axial Slots) (Ref. 119)



DEFECT NO.	TYPE	LOCATION	DEPTH[a] (% OF WALL)
1	Hole (0.0254 mm or 0.010 in. dia)	--	100%
2	EDM[b]	OD	80
3	"	"	60
4	"	"	40
5	"	"	20
6	"	"	10
7	"	"	100
8	"	ID	80
9	"	"	60
10	"	"	40
11	"	"	20

(a) Tube wall thickness = 0.381 mm (0.015 in.)
(b) Electric discharge machined (EDM) defect

FIGURE 9.18. Typical Strip Chart Recording of Differentiated Eddy-Current Output (Test Standard-Circumferential Slots) (Ref. 119)

the reference hole is scanned each time a fuel rod is inspected. Periodic recalibration of the system assures the operator that the system is operating at the desired level.

9.6.6 Fuel Rod Acceptance and Rejection Criteria

Eddy-current results, along with ultrasonic and other supplemental test (e.g., visual) results, are compared by the fuel vendor with his acceptance and rejection criteria for irradiated fuel rods.

9.6.6.1 Eddy-Current Test Results

The eddy-current test results are used to assess the leak-tight integrity of irradiated fuel rods. Criteria for the acceptance and rejection of fuel rods are based on the amplitude response from the defect standard. Strong eddy-current signals in the areas of the fuel rod that were between the spacer grids would indicate the presence of a potential through-wall defect and are a likely cause for rejection of the fuel rod (see Figure 9.18). Smaller amplitude signals typically correspond to defects that are partial through-wall defects.

Strong amplitude signal indications are characteristic at the spacer grid areas on fuel rods because of fretting wear; however, defects in these areas can be difficult to distinguish. Visual inspection is used to determine the surface condition of the fuel rod at the spacer grid areas. If fretting wear is determined to be the cause of these indications, the fuel rod may be rejected, depending on the degree of cladding degradation.

9.6.6.2 Ultrasonic Test Results

As will be discussed in Section 10, one vendor uses ultrasonic inspection to confirm the presence of water in an irradiated fuel rod, which is an indication of loss of fuel rod integrity. Ultrasonic test sensitivity is not affected by the same variables that influence the detection sensitivity of the eddy-current test.

9.6.6.3 Visual Inspection Results

One vendor stated that there was a high probability of visually confirming the presence of a defect that produced large amplitude eddy-current signal indications. For smaller amplitude indications, there is a low probability (10%) of visually confirming the presence of the defect(s).

Visual inspection is the principal means of assessing damage in the fuel rod end cap weld areas because eddy-current testing is not performed in these areas of the fuel rod.

Vendors reported that on limited occasions surface penetrating defects were confirmed by visual inspection; however, the eddy-current test results showed little or no signal indication from these defects. One vendor stated that small pinhole defects were difficult to detect using eddy-current testing. These pinhole defects sometimes emit bubbles that can be detected visually.

9.6.6.4 Rejects Due to Handling

Vendors stated that fuel rods are rejected if they have been dropped or excessively bowed or bent as a result of handling operations.

9.6.7 Frequency of Eddy-Current Inspection

Eddy-current testing is not routinely used during fuel surveillance programs. In interviews with the various fuel vendors, it was noted that each fuel surveillance program is unique; therefore, the inspection methods used at one outage may not be selected for use at the next outage. One fuel vendor does not perform eddy-current tests at poolside. Two fuel vendors indicated that they seldom use eddy-current testing at poolside. Another fuel vendor indicated that eddy-current testing was included in their fuel surveillance programs when it was suspected that fuel failures were present or when lead test bundles were to be inspected to provide data on fuel design.

Basically, eddy-current testing is employed in two cases. The first is when there are potential leaker fuel rods in fuel bundles that need to be detected and characterized as leakers and replaced. Traditionally the reliable method for predicting potential fuel failures is through the continuous monitoring of the plant off gas. If the plant off gas indicates a potential leaker condition then eddy-current inspection may likely be selected for use during a reactor refueling outage. However, one vendor indicated that even if fuel bundles are found to be leaking, the bundle will not necessarily be disassembled and each rod eddy-current tested. The vendor may elect to forego this inspection operation and replace the leaker bundles with new bundles. Conversely, if the plant off gas indicated no potential for leakers, eddy-current inspection would not be used.

The second case when eddy-current testing is used is during the extended or lead fuel surveillance programs. These programs are directed toward the introduction of new fuel designs. Lead fuel bundles are selected to undergo extensive nondestructive, visual, and dimensional characterization. As part of this testing, a limited number of rods receive eddy-current inspection.

Table 9.1 shows a list of the domestic fuel vendors who perform eddy-current inspections at poolside and the associated total number of fuel rods inspected to date. As noted in Section 4, some fuel bundles are designed so they can be readily disassembled. This feature is important from a nondestructive testing standpoint: if the bundle cannot be disassembled, testing of individual fuel rods cannot be performed without destruction of the bundle structure.

TABLE 9.1. Poolside Eddy-Current Inspection of Irradiated LWR Fuel

	Data from Fuel Vendors				
Type of Fuel Manufactured	PWR	PWR	PWR/BWR	BWR	PWR
Approximate Number of Irradiated Fuel Rods Inspected by Eddy-Current Testing	--	400[a]	500	43,000	Unknown

(a) Approximately 200 burnable poison rods also examined.

9.6.8 Time and Personnel Requirements

Vendor estimates of the time required to complete an eddy-current test on a single rod ranged from a few minutes to an hour. Vendors stated that often eddy current is not the only test being performed at poolside. In addition to the eddy-current test, visual, dimensional, ultrasonic, and gamma scan measurements can be performed at the same time. The merit of performing several examinations at once minimizes the need to handle and move the fuel rod. If eddy current testing were the only examination being performed on the fuel rod, a complete inspection could be performed in well under one minute. Vendors indicated that the eddy-current test is a rapid means of volumetrically inspecting fuel rods; however, the time-consuming part of the inspection really

involves the bundle disassembly (see Tables 5.6 and 8.6), rod extraction, rod reinsertion, movement of the rod to and from the test station, calibration, supplemental inspection, and interpretation of data.

Vendors estimate that it requires two technicians per shift to perform eddy-current testing. During the more detailed fuel surveillance programs, there are a number of technicians and some engineers participating in these programs. The technicians are used in performing the overall fuel inspection program and are not dedicated to performing eddy-current inspection alone.

9.7 Limitations to Eddy-Current Testing

One limitation of eddy-current testing as practiced at poolside is the lack of sensitivity and reliability for detecting incipient defects. Incipient defects are characteristically very tight cracks that initiate at the cladding ID and can eventually penetrate through the cladding wall. One cause of incipient defects in the cladding is pellet-cladding interaction. Recent studies on this phenomenon involved eddy-current testing at poolside and in the hot cell to detect potential incipient defects. Nondestructive eddy-current and destructive metallographic results from those studies showed that an eddy-current signal is much less likely to indicate cracking than it is to indicate fuel-cladding bonding, pellet fragmentation, and/or cladding ridging.

Several vendors indicated that incipient defects are difficult to detect. They question the reliability of the eddy-current measurement for incipient defect detection because they have destructively sectioned fuel rods with strong eddy-current signals and have not found defects. Another vendor indicated that they had examined approximately 20 irradiated fuel rods in an effort to correlate eddy-current signals with the results obtained from metallography. The results of this study showed that there was no defect size correlation.

Vendors stated that analysis of eddy-current data from fuel rods can be difficult because of cladding ridging, fretting about the spacer grid area, scratches, bulging, oxide, and crud deposits. Confirmation by supplemental techniques are needed; this requires additional time and personnel.

The end cap weld areas on fuel rods cannot be inspected using the present poolside eddy-current techniques. The visual inspection used to inspect those areas requires additional time and personnel.

9.8 Poolside Inspection Hazards

Eddy-current inspection does not alter its subject specimen. However, vendors reported that there have been instances when fuel rods have hung up in the encircling coil probe.

It appears that the greatest potential hazard to the integrity of a fuel rod is not the eddy-current inspection itself but the remote handling operations that are required in performing the inspection. On several occasions fuel bundles have been dropped. Fuel rods have also been dropped. Once a fuel rod is removed from its position in the bundle, it must be moved very carefully to the eddy-current inspection station so as not to bow, bend, or drop the rod. Rod withdrawal and reinsertion can cause scratching of the outer surface of the fuel rod cladding.

One fuel vendor reported (Ref. 120) that increased handling of an irradiated fuel bundle, such as that experienced when the bundle is transferred temporarily from the primary containment to the spent fuel storage pool and then moved back to the reactor core, coupled with a large absolute local power increase in the subsequent reactor cycle, increases the probability of fuel rod perforation.

9.9 Hot Cell Eddy-Current Inspection Techniques

9.9.1 Use of Hot Cell Inspection

Nondestructive eddy-current and confirmatory destructive testing of selected fuel rods is performed in hot cells to provide detailed characterization of fuel performance phenomena. Specifically, the nondestructive/destructive test data derived from hot cell examination of fuel rods provides valuable feedback information to field inspection personnel. The destructive examination data are needed to determine test confidence (detectability, reliability, defect severity, adequacy of standards) and to better understand the often complex fuel degradation mechanisms that nondestructive techniques are attempting to detect and measure.

Selection of fuel rods for hot cell examination can be based on the poolside inspection results. The rods are destructively sectioned where eddy-current

signals indicate the presence of defects. The metallographic results from the destructive examination provide detailed data defining defect type, length, width, depth, and location.

The eddy-current inspection systems used at hot cells differ from the continuous wave, single-frequency, sinusoid excitation systems used at poolside. Recently published reports from fuel performance programs sponsored by the Electric Power Research Institute show hot cell eddy-current test results from irradiated LWR fuel inspection using a two-frequency, eddy-current system (Refs. 39, 72, 121, and 122). Researchers at Idaho National Engineering Laboratory (INEL) (Ref. 123) and General Electric Vallecitos Nuclear Center (GEVNC) (Ref. 124) reported results of their hot cell inspection programs for irradiated LWR and breeder reactor fuel using pulse eddy current (PEC) systems. Much of the reported PEC hot cell work to date has been the result of research programs investigating LWR and breeder reactor fuel rod performance.

9.9.2 Pulsed Eddy-Current Inspection

Sinusoids are but one of many current wave forms that can be used to provide excitation to the inspection probe coils. A repetitive pulse excitation (e.g., square wave), where the pulses are repeated in rapid succession (1000 pulses/second), can also be used to generate eddy currents. The PEC system provides a series of current pulses to the inspection probe, inducing eddy currents in the object under test. The induced eddy currents produce a corresponding pulsed magnetic field that induces a voltage pulse in the inspection probe coils. During operation, the induced voltage pulse can be time-sampled to distinguish between the outer and inner cladding surfaces. Only outer surface information is inherent in the initial portion of the voltage pulse. The latter portion of the pulse contains information on both the cladding outer and inner surface and wall thickness. The system is designed such that sampling gates make it possible for the initial portion of the returning voltage pulse to be displayed at one output channel, while the latter portion of the voltage pulse is displayed on a second channel as shown in Figure 9.19 (Ref. 124). If portions of the signal appear on both channels, the position of the defect can be estimated from the relative signal strength of each channel.

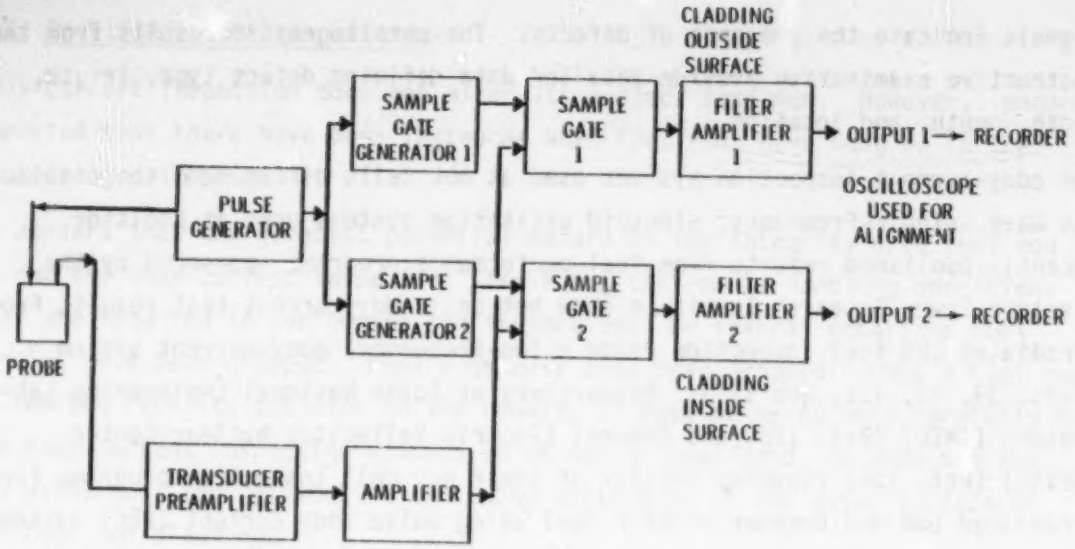


FIGURE 9.19. A Pulsed Eddy-Current System (Ref. 124)

The PEC system at INEL employs three inspection probes. An encircling coil probe is used to inspect full length fuel rods for inner and outer cladding surface defects and for average wall thickness. Two point probes were used, one to measure wall thickness and the other for defect inspection. The point probes are designed so that the electromagnetic search field of the coil is active only over a small area of the test object. Because the search field is small, defects have a greater effect on the coil response.

There are disadvantages to the use of point probes at poolside compared to hot cell inspection. Because of the small search field of the point probe (e.g., 10^{o} radial arc) a complete 100% volumetric inspection would require many rod scans. For example, at 10^{o} increments at least 36 scans would be required for a single inspection. Sensitivity of detection is a function of the scan speed. The optimum scan speed for the PEC system at INEL is 7.62 cm/sec (Ref. 123). LWR fuel rods typically have an active fuel length of 366 cm. Therefore, a single 10^{o} arc scan would take 48 sec to complete. A complete volumetric inspection would take approximately 30 min to complete.

However, there are considerably more data to handle and evaluate when using the point probe technique. This adds to the time required to complete the inspection and must be considered when performing poolside inspection. These time constraints are not encountered during hot cell inspection.

9.9.3 Pulsed Eddy-Current Inspection of Unirradiated Fuel

Reference 123 shows the PEC test results from the inspection of artificial defects in unirradiated fuel rod cladding using both encircling and point probes. Two EDM defect standards were fabricated from Zircaloy fuel rod cladding with an outer diameter of 1.42 cm and wall thicknesses of 0.081 cm and 0.094 cm, respectively. Both axial and transverse EDM slots, 0.254-cm long by 0.003-cm wide, at depths of 0.005, 0.010 and 0.015 cm were included in the defect standards. The test results obtained with the encircling coil at a scanning speed of 7.62 cm/s are shown in Figure 9.20 (Ref. 123). The encircling coil had greater sensitivity to axial slots than transverse slots. Figure 9.20 shows that the system is capable of detecting a 0.005-cm deep slot on the OD and a 0.010-cm deep slot on the ID in both defect standards.

Figure 9.21 shows the encircling coil response to the wall thickness standard fabricated from a 1.42-cm diameter, Zircaloy-clad fuel rod (Ref. 123). The inside diameter changed in 0.006-cm steps that were 1.27-cm long so the wall thickness ranged from 0.068 cm to 0.106 cm.

The point probe used for defect inspection was originally designed for fuel rods with a wall thickness of 0.076 cm. Because the wall thickness of the standards was greater than the design specification of the point probe, the point probe depth of penetration (sensitivity to inner surface defects) was limited. Figure 9.22 shows the response of the point probe to the EDM slot standards (Ref. 123). In comparing these data with that of the encircling coil, it would appear that the encircling coil system has equal sensitivity for the detection of outer diameter defects, and quite likely has equal sensitivity for detection of inner wall defects (an improved point probe will be fabricated for future testing).

Figure 9.23 shows data from a 28-cm long section of an LWR fuel rod using both the encircling coil probe and the point probe (Ref. 123). It was noted that

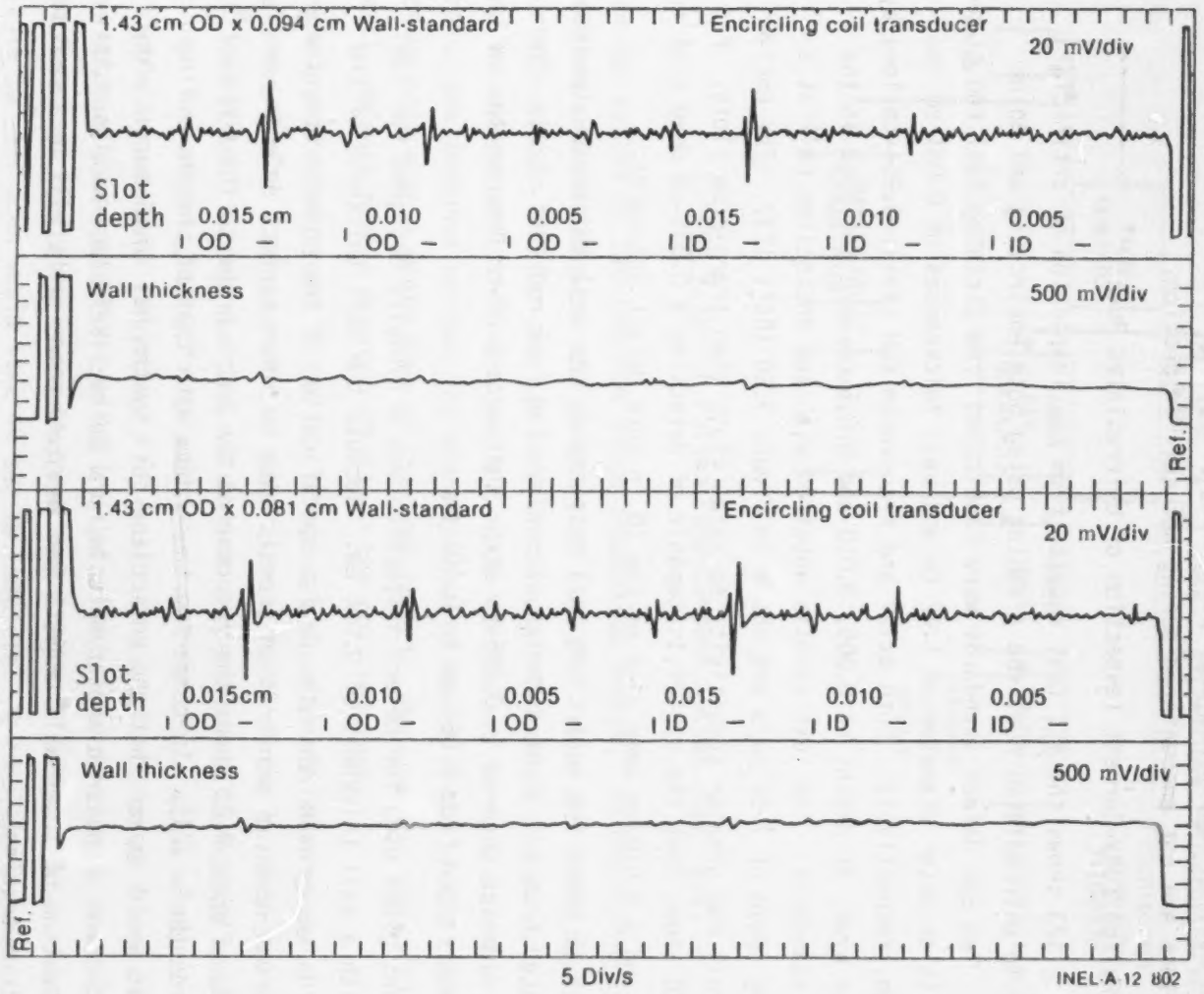


FIGURE 9.20. Response of Encircling Coil Transducer to the Test Standard (Ref. 123)

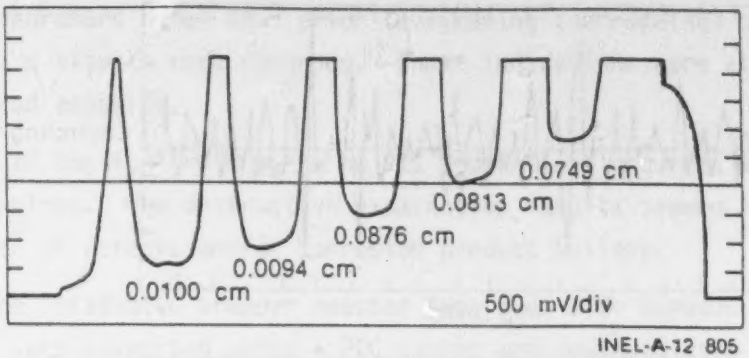


FIGURE 9.21. Response of Encircling Coil Transducer to the Wall Thickness Standard (Ref. 123)

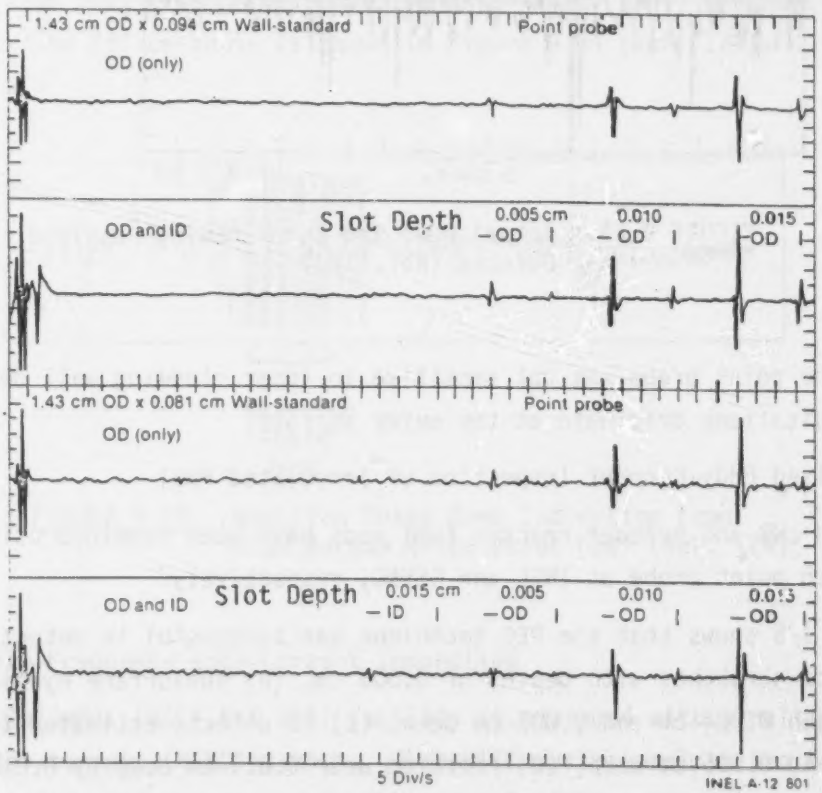


FIGURE 9.22. Response of Point Probe to the Test Standard (Ref. 123)

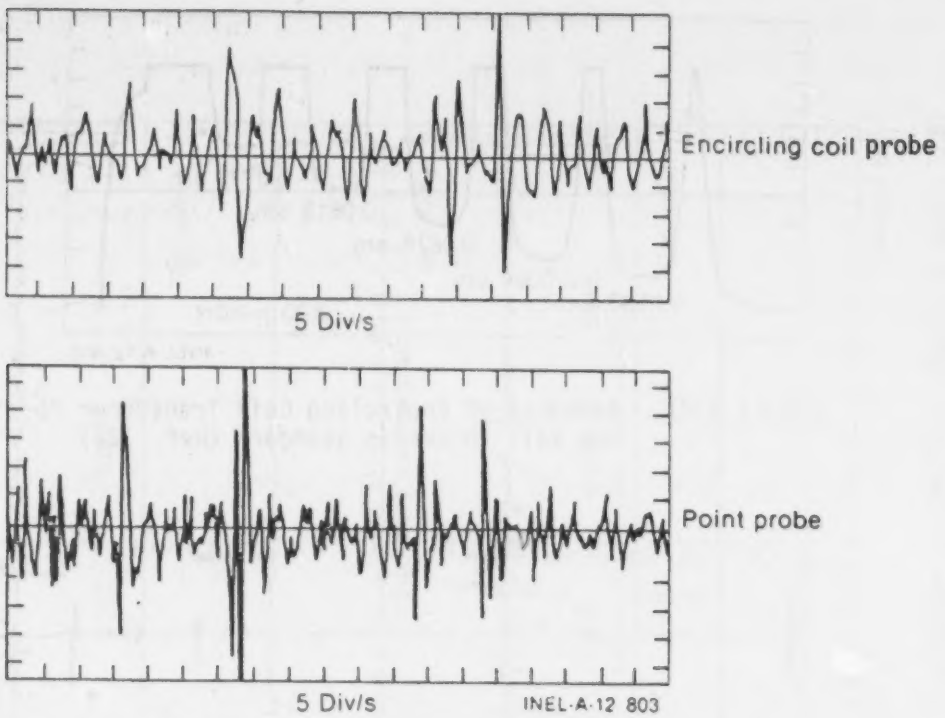


FIGURE 9.23. Actual Fuel Rod Scan Showing Possible Defects (Ref. 123)

because the point probe was not sensitive to inner cladding wall defects, these defect indications originate at the outer surface.

9.9.4 Pulsed Eddy-Current Inspection of Irradiated Fuel

Irradiated LWR and breeder reactor fuel rods have been examined using a PEC system with point probe at INEL and GEVNC, respectively.

Reference 125 shows that the PEC technique was successful in detecting: (a) surface scratches with depths of 0.005 cm, (b) subsurface hydride degradation between 0.004-cm and 0.007-cm deep, (c) ID defects estimated to be between 0.002-cm and 0.005-cm deep, (d) fretting wear 0.013-cm deep by 0.015-cm wide, and (e) small (0.038 cm) corrosion product buildup. Note that either the small hydride defect or the small corrosion product buildup were sufficient to cause defect indications. Unlike poolside inspection, the fuel rods examined at INEL were first chemically cleaned to remove surface corrosion product (crud)

deposits. Researchers noted that prior to cleaning (decrudding) of the rods, many defect-like signals were recorded. These indications were attributed to the surface crud deposits.

Several areas of the fuel rods where no PEC indications occurred were also destructively examined. The destructive examination results showed that these areas were free of defects and/or corrosion product buildup.

At GEVNC, three irradiated breeder reactor fuel rods with burnups of 4752 GJ/kg (1320 Mwh/kg) were inspected using a PEC system and destructively examined (Ref. 124). In this study researchers reported the PEC technique was very sensitive to OD surface anomalies (scratches, corrosion product deposits, etc.). One interesting result showed the PEC technique detecting a 0.001-cm deep chemical reaction phase zone (fuel-cladding interaction zone) that encircled the fuel rod. The PEC response is shown in Figure 9.24 (Ref. 124).

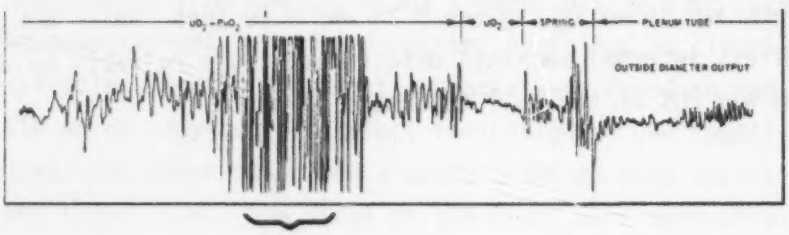


FIGURE 9.24. Reaction Phase Zone Indication from High Burnup Mixed Oxide Fuel (Ref. 124)

9.9.5 Multiple-Frequency Eddy-Current Inspection

The Battelle Columbus (BCL) hot cell facility is equipped with a multiple-frequency, eddy-current (MFEC) system. That MFEC system employs two frequencies. The facility is also equipped with a single-frequency system. The MFEC principle of operation and equipment description are similar to those of the single-frequency eddy-current system used at poolside. When testing with an

MFEC system, more information is obtained for a given inspection because more than one frequency of inspection is used. Frequencies of 100 kHz and 700 kHz were used for the inspection of LWR fuel at BCL.

9.9.6 Multiple-Frequency Eddy-Current Inspection For Irradiated Fuel

Results from several LWR fuel performance programs conducted at BCL have been reported in the literature. Many fuel rods were inspected using single-frequency eddy current at poolside as a means of selecting rods for detailed hot cell examination. Potential incipient defect indications were of particular interest.

Standards were fabricated from Zircaloy fuel cladding for system calibration and defect sizing. The standard was composed of external and internal EDM slots, a through-wall hole, a ridge, and a uniform circumferential thinned region. The response to the machined defects in the standard for the single-frequency (encircling coil probe) and multiple-frequency (point probe) eddy-current systems are shown in Figures 9.25 and 9.26 (Ref. 39). BCL reported that the smallest internal machined defect that could reliably be detected with either system was 20% of the wall thickness in depth.

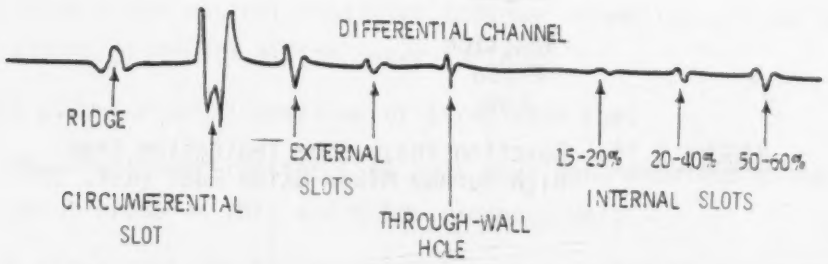


FIGURE 9.25. Typical Scan Obtained on Test Standard Using Encircling Coil Probe Eddy-Current System at 500 kHz (depth of internal slot shown as percent of wall thickness) (Ref. 39)

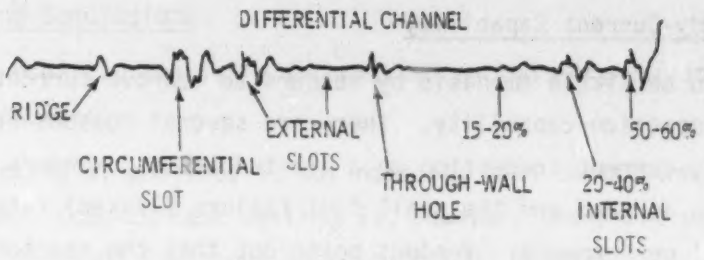


FIGURE 9.26. Typical Scan Obtained on Test Standard Using Point Probe and Multiple-Frequency System (depth of internal slot shown as percent of wall thickness) (Ref. 39)

The multiple-frequency system at BCL employs a point probe that inspects approximately a 60^{o} circumferential arc per scan of the rod. The point probe was used because it provided information on the circumferential position of defects on the cladding wall.

A summary of the results from the BCL study showed that in most cases, locations of strong eddy-current defect indications contained no cladding defects; however, fuel-cladding bonding did exist. Cracks were found in two cases that had shown little or no eddy-current defect indications. One sample contained two radial cracks; the other contained a small 0.005-cm deep defect. These cracks were very tight (i.e., the sides of the crack were very close together).

Other results showed that there were cracks present in the cladding as indicated by the eddy-current test. However, these cracks were much wider (i.e., sides of crack were not close together) and filled with corrosion products compared to the tight cracks that were not detected.

Based on the results from this study, BCL investigators concluded that an eddy-current indication is much less likely to reflect cladding cracks than it is to reflect fuel-cladding bonding, cladding ridging, or fuel-cladding mechanical interaction. Tight cracks are difficult to detect and may propagate through the cladding wall without being detected. Wide cracks are more likely to be detected.

9.10 Future Eddy-Current Capability

There appears to be little emphasis by vendors to improve current poolside eddy-current inspection capability. There are several reasons for this. Most vendors use eddy-current inspection on a limited basis. Vendors stated that fuel performance is good and the small fuel failure (leaker) rate is indicative of the good fuel performance. Vendors point out that the reactor system was designed to have some leaker rods in the core during normal plant operation. Present eddy-current testing capabilities have proven to be adequate for detecting leaker rods during poolside inspection.

One fuel vendor is currently studying the possible use of multiple-frequency methods for inspection of irradiated fuel rods at poolside. Such methods could be used to improve inspection and help simplify data analysis by alleviating unwanted signal information that can complicate interpretation of results. In addition, work is continuing at INEL to improve PEC techniques.

It is probable that inspection probes can be fabricated to provide improved detection sensitivity to incipient type defects without sacrificing the need for simplicity and high scan speed. Probes could also be fabricated to inspect fuel rod end cap weld areas.

Vendors indicate that they do not now use eddy-current pattern phase information to determine defect depth (the pattern phase angle is a function of the defect depth). However, two vendors indicated that they were going to attempt to use pattern phase information in the future. Reference 57 shows how the interpretation of signals was aided by the ability to "phase out" (cancel) the effects of cladding ridging.

Present PEC and multiple-frequency eddy-current systems generate greater quantities of data than the single-frequency eddy-current systems. Computer methods for the data handling and analysis would seem to be a logical approach to the handling and processing of this information. Recent studies have shown the potential for automated computer signal analysis of eddy-current data (Refs. 126, 127, and 128).

A foreign reactor vendor has developed an eddy-current probe to measure cladding external oxide layer thickness (Ref. 1).

9.11 Summary and Conclusions

There is little publicly available information on the eddy-current inspection of LWR fuel at poolside.

Eddy-current testing at poolside is not normally used during the interim refueling outage. Eddy-current testing is, however, the principal method used to detect leaky (failed) fuel rods in suspect fuel bundles. Because of the good fuel performance trends over the past five years, only a small number of fuel rods have undergone eddy-current inspection. Eddy-current testing is continuing to be used at poolside during the more extensive fuel examination programs with lead fuel bundles; however, the number of these detailed inspection programs conducted per year is limited. Eddy-current testing in hot cells is limited because few bundles are scheduled to receive detailed postirradiation analysis.

9.11.1 Eddy-Current Inspection Comparisons

The following conclusions about poolside eddy-current inspection can be drawn:

- The eddy-current test is a rapid means of inspecting fuel rods to assess their leak-tight integrity.
- The analysis of single-frequency data can be a tedious and subjective task.
- Supplemental techniques (visual, ultrasonic, LVDT) are used to help assess the condition of the fuel rod.
- Defect standards for eddy-current testing are similar among fuel vendors in that the standards are composed of electric discharge machined (EDM) slots on the cladding ID and OD and at least one through-wall hole.
- Test systems employed at poolside are single-frequency, continuous wave excitation, eddy-current systems.
- Encircling coil differential probes are used for poolside inspection.
- Eddy-current information is stored on a dual channel strip chart recorder and/or a magnetic tape recorder.

- Fuel vendors consider the eddy-current test procedures and the evaluation criteria for accepting or rejecting fuel rods to be proprietary information. The test procedures and evaluation criteria are different for each vendor.
- Fuel vendors use different supplemental techniques (e.g., visual) to assist in assessing the condition of fuel rods.
- Reporting of eddy-current test results is not uniform among vendors.
- Not all vendors agree that the current single-frequency systems used at poolside are adequate for fuel inspection.
- The amount of eddy-current inspection experience at poolside varies considerably among the fuel vendors.
- Fuel vendors stated that there is a general uncertainty as to the severity of a defect indication. This is a result of the lack of correlation between eddy-current indications and the information from detailed metallographic examinations.
- In past years, heavy crud deposits on fuel rods presented a problem for eddy-current inspection and in the interpretation of those inspection results. This heavy crud buildup problem has reportedly subsided, a result of improved water chemistry control.
- Vendors stated that there was a high probability of visually confirming the presence of defects where strong eddy-current signal indications had occurred. Defects producing small eddy-current indications have a low probability of visual confirmation.
- Vendors expressed confidence in their ability to detect fuel rods with breached cladding using poolside eddy-current inspection systems.
- Eddy-current testing of fuel rods at poolside during a reactor outage can be limited by critical path restraints.

The following conclusions about hot cell eddy-current inspection can be drawn:

- Most fuel vendors have in-house hot cell facilities; however, few of those facilities can accommodate full-length commercial LWR size fuel rods.
- Single-frequency, multiple-frequency, and pulsed eddy-current systems are being used on a limited basis for postirradiation inspection of fuel rods.
- Both pulsed eddy-current and multiple-frequency eddy-current testing are considered by fuel vendors to be research and development techniques and are only used in the hot cell.

9.11.2 Failed Fuel Comments

Eddy-current testing is the principal nondestructive technique used for the 100% volumetric inspection of the fuel rod cladding. Strong eddy-current signals on fuel rods between the spacer grid areas are an indication of a possible breached cladding condition. Criteria for accepting and rejecting fuel rods depend on eddy-current and supplemental test results. Fuel rods which are known to have or are suspected of having a breach in the cladding are rejected. Vendors stated that visual inspection has detected bubbles being emitted from the surface of fuel rods, which when inspected by an eddy-current technique showed no defect indications. Visual inspection is an important supplemental technique for assessing fuel rod damage in the spacer grid areas. Vendors indicate that fretting wear on fuel rods at the spacer grid areas can be cause for fuel rod rejection.

10. ULTRASONIC INSPECTION

10.1 Introductory Comments

Ultrasonic testing is a nondestructive measurement technique used to determine the leak-tight integrity of irradiated fuel rods and to detect suspect failed fuel rods. Two domestic fuel vendors indicated that they had investigated the use of ultrasonic testing in attempts to detect coolant entry into the fuel rod; however, they currently do not use ultrasonic techniques at poolside. Only one domestic fuel vendor uses ultrasonic testing at poolside to detect water within the fuel rod, an indication that the cladding has been perforated. One foreign company uses an approach similar to that of this domestic fuel vendor; however, their technique involves heating and cooling of the fuel rod. This application is discussed later.

The presence of water within the fuel rod causes a change in the ultrasonic signal amplitude when the water contacts the inner cladding wall surface. One domestic fuel vendor has inspected thousands of fuel rods using this technique and indicated that it has detected leaky fuel rods. When water is detected in a fuel rod, the rod is categorized as failed (leaker) and is replaced with another fuel rod during reconstitution of the fuel bundle.

Recently, there have been additional applications of ultrasonic testing techniques to poolside inspection. Another of the domestic fuel vendors reported that they had attempted to use ultrasonics to inspect fuel rods for axial defects in the cladding wall. In addition, they have attempted to use ultrasonic testing to determine if fuel pellets were bonded to the cladding.

10.1.1 Ultrasonic Testing Principles

Ultrasound is sound wave energy generated at ultrasonic frequencies (i.e., greater than 20,000 Hz) by the application of a high voltage pulse to a piezoelectric material. It is through this phenomenon, called the "piezoelectric effect," that electrical energy is converted to mechanical energy (and vice versa) to produce and detect sound waves at high frequencies. The piezoelectric effect has a forward (generation) and reverse (detection) effect. Figure 10.1 shows an example of the forward piezoelectric effect where a voltage

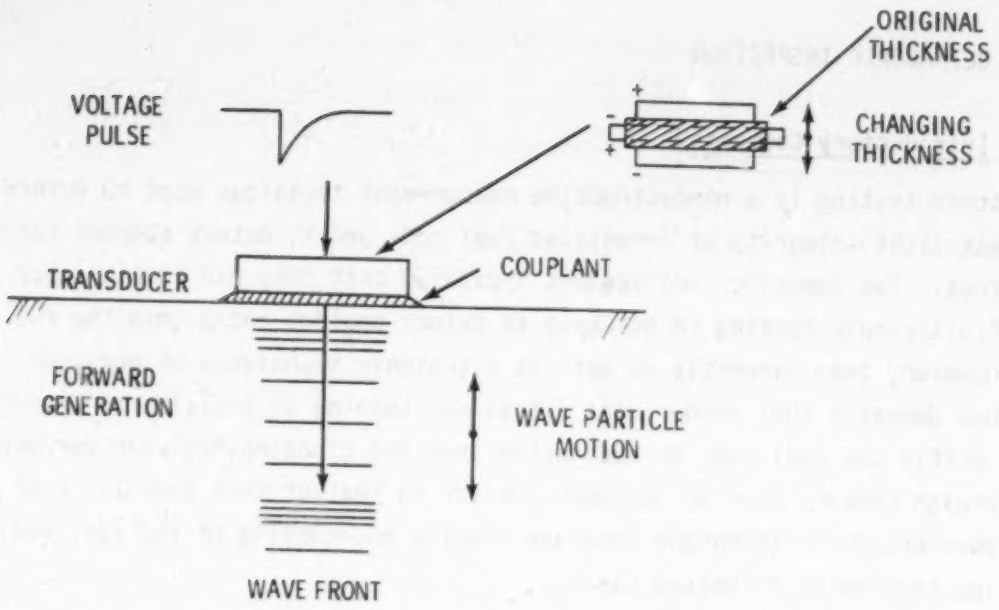


FIGURE 10.1 Forward Piezoelectric Effect (Electric Signal Input - Mechanical Thickness Change - Acoustic Sound Pressure)

pulse is applied to the piezoelectric crystal (transducer). This sharp voltage pulse causes the piezoelectric crystal to expand and contract from its original thickness. The electric pulse energy has been converted into mechanical sound vibrations due to the piezoelectric effect. If the voltage pulses are repeated in rapid and periodic succession, a series of sound waves will be continuously transmitted from the piezoelectric transducer. In order to transmit the sound wave energy into the test material, a liquid (water) provides a couplant path for the sound to travel from the transducer, through the couplant liquid, and into the material under test. Liquid couplants are used because of their convenience. The reverse (detection) effect is shown in Figure 10.2. The returning sound waves create a stress (pressure wave) on the transducer, which causes a voltage change to occur in the piezoelectric material.

There are two types of sound waves used for ultrasonic fuel inspection at poolside: longitudinal and shear waves. Longitudinal waves are compressional waves and have characteristic compressional and rarefaction particle

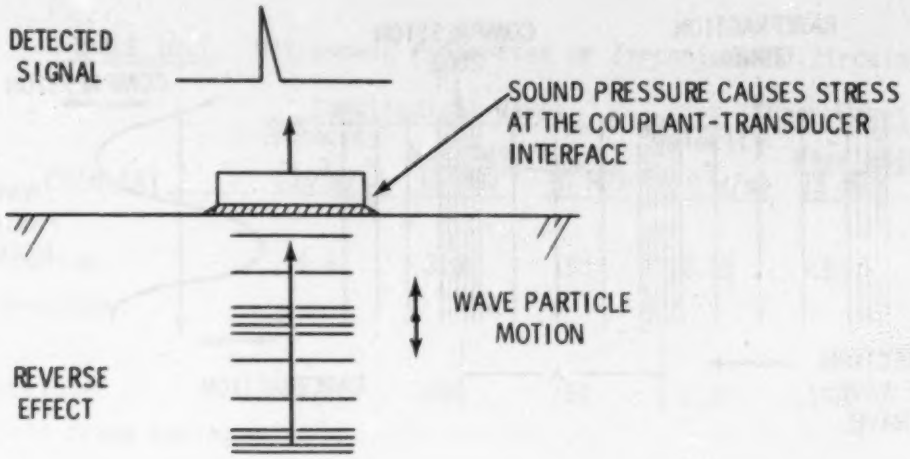


FIGURE 10.2. Reverse Piezoelectric Effect (Acoustic Sound Pressure - Mechanical Thickness Change - Electric Signal Output).

displacement zones, as shown in Figure 10.3. The particle motion (atomic scale) is in the same direction as the wave front propagation. Unlike longitudinal waves, shear waves do not have rarefaction or compressional zones (Figure 10.4). Shear waves have particle motion that is orthogonal (shearing action) to the wave propagation direction.

The velocity of longitudinal sound waves can be calculated from equation (1),

$$v = \lambda f \qquad (1)$$

where v = longitudinal wave velocity, λ = distance of one wave length, and f = frequency of oscillation.

The velocity of a shear wave is approximately one-half that of the longitudinal wave. The wave length (λ) is an important parameter because the minimum detectable size of a defect is approximately the wave length of the sound used. Using equation (1), and given the material to be inspected, the wave length of sound can be calculated for different inspection frequencies. Calculations for Zircaloy cladding are shown in Table 10.1. Note that detection of small cladding defects requires frequency selection in the megahertz region (ultrasonic region). For shear waves at 30 MHz in Zircaloy-4 cladding, the minimum detectable defect size is 81 μm.

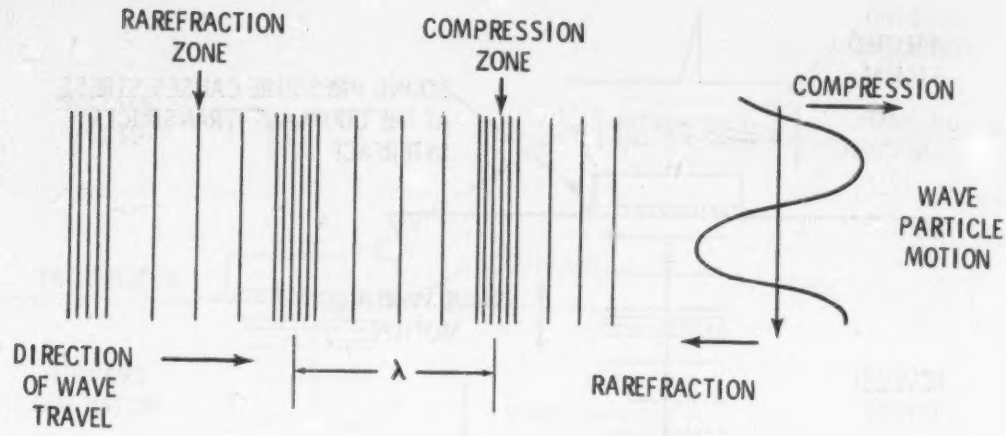


FIGURE 10.3. Longitudinal Wave. (Wave particle motion and resulting compression and rarefraction zones. The wavelength, λ, is the distance corresponding to a complete cycle.)

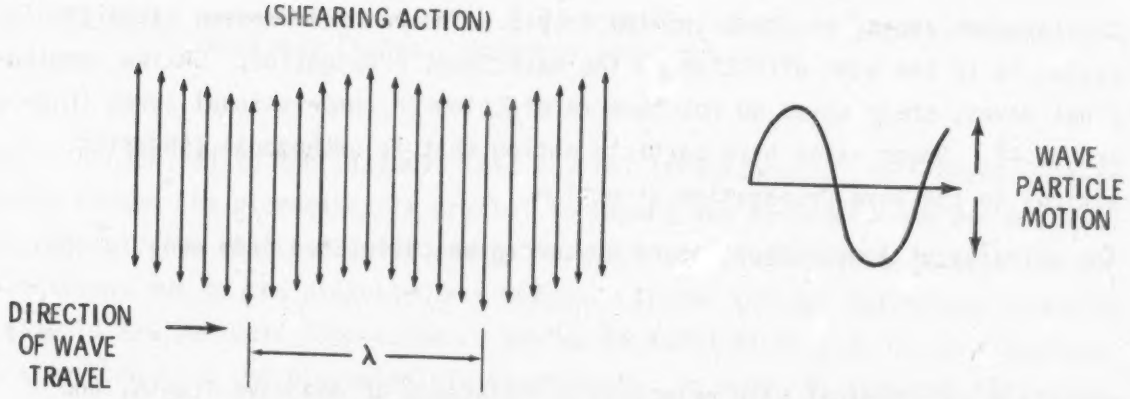


FIGURE 10.4. Shear Wave. [Wave particle motion (shearing action); no compression or rarefraction zones.]

A most important property of ultrasound is its inability to completely traverse an unfavorable acoustic boundary, such as a crack or other anomaly embedded in the test material. This concept is illustrated in Figure 10.5 where a percentage of the total sound energy is reflected back to the sending transducer. Because of this unique property of ultrasound, defects in materials can be detected.

TABLE 10.1. Ultrasonic Properties of Zirconium and Zircaloy

Material	Longitudinal Waves			Shear Waves		
	Velocity (10^3m/s)	Wavelength (μm) 15 MHz	30 MHz	Velocity (10^3m/s)	Wavelength (μm) 15 MHz	30 MHz
Zirconium annealed	4.6	310	155	2.25	150	75
Zircaloy-2 cold drawn tubing	4.62	308	154	2.34	156	78
Zircaloy-4 cold drawn tubing	4.53	302	151	2.44	162	81

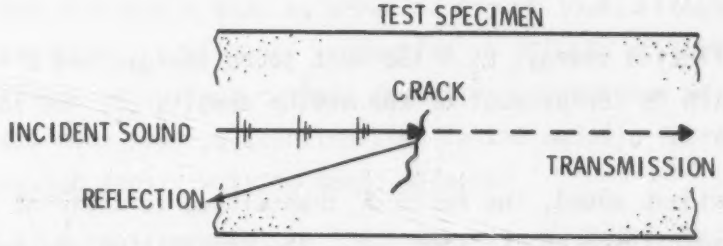


FIGURE 10.5. Incident Sound Energy at Crack Interface Partially Reflected and Transmitted

Whenever ultrasonic waves strike the interface of two different materials (such as the water-fuel cladding interface or the fuel pellet-cladding interface) a percentage of the sound energy is reflected (E_r) and transmitted (E_{tr}). At some acoustic boundaries the incident sound energy (E_i) is totally reflected. Figure 10.6 shows the interface between two mediums, with ultrasonic energy being reflected and transmitted from medium I to medium II. For normal incident sound, the ratio of reflected to incident sound is called the reflection coefficient, αr:

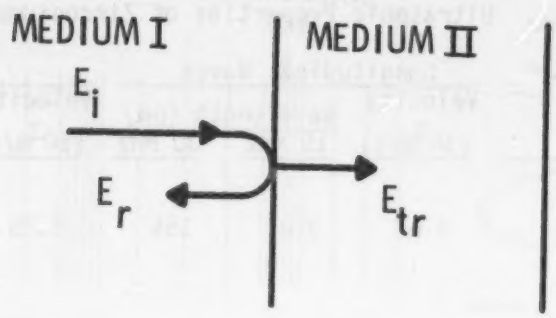


FIGURE 10.6. Sound Energy Transmission Between Two Mediums

$$\alpha r = \frac{E_r}{E_i} = \left[\frac{Z_1 - Z_2}{Z_1 + Z_2}\right]^2 \qquad (2)$$

where E_r = reflected energy, E_i = incident sound energy, and Z = acoustic impedance, which is the product of the medium density (ρ) and sound velocity (V).

For normal incident sound, the ratio of transmitted to incident sound is called the transmission coefficient, αt. The transmitted and reflected energy must equal the incident energy; therefore,

$$\frac{E_r}{E_i} + \frac{E_{tr}}{E_i} = 1 \qquad (3a)$$

$$\alpha r + \alpha t = 1 \qquad (3b)$$

As the acoustic impedance of medium I approaches that of medium II, E_{tr} increases.

10.2 Ultrasonic Test System

Ultrasonic test systems used at poolside are composed of three major subsystems, including: a) piezoelectric transducer, b) ultrasonic instrument, and c) data recording and display instruments. A basic block diagram of the system is shown in Figure 10.7.

FIGURE 10.7. Block Diagram of Ultrasonic Test System

One fuel vendor stated that they had developed their own ultrasonic test instrument to meet their specific testing needs. Another fuel vendor uses a commercially available instrument and employs the oscilloscope cathode ray tube (CRT) display to interpret signal data.

10.2.1 Transducer

Focused ultrasonic transducers are used for poolside fuel inspection. The addition of an acoustic lens element to the front face of the transducer causes a focusing of the ultrasonic beam as shown in Figure 10.8. Focused transducers have several advantages, including: reduction in effects of surface roughness, reduction in effects of surface contour (geometry), reduction of metal noise (echo reflections from small discontinuities in the metal), increased resolving power, and increased sensitivity to small defects.

The transducer is a key component in the inspection system. Through the piezoelectric phenomenon, the transducer is the link between the specimen being tested and the system instrumentation used to perform the testing. The single element transducers used for poolside inspection vary in size (diameter) and

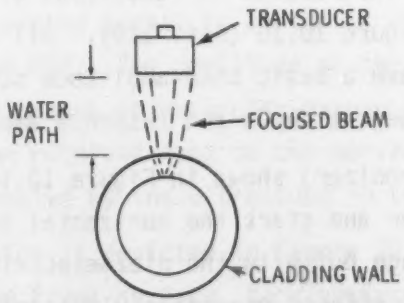


FIGURE 10.8 Focused Ultrasonic Transducer

design frequency of operation. Poolside inspection requires that the transducer(s) be placed in an adjustable head fixture that is submerged. The transducers are sealed in a metal case and are essentially unaffected by the high radioactivity levels experienced during poolside testing.

A typical cross-sectional view of a transducer is shown in Figure 10.9 (Ref. 129). The piezoelectric crystal fits securely into the machined metal case. One face of the crystal is grounded to the metal case while the other is connected to the "hot" lead. The "hot" lead is connected to the instrument pulser, which supplies a high voltage excitation pulse to the piezoelectric crystal.

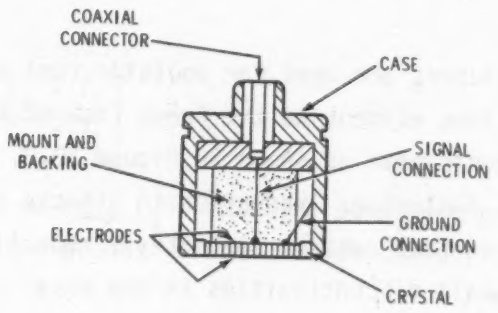


FIGURE 10.9. Ultrasonic Transducer (Ref. 129)

10.2.2 Signal Processing

The generation and electronic processing of ultrasonic signal information is done with the ultrasonic instrument. A functional diagram of a pulse-echo instrument is shown in Figure 10.10 (Ref. 129). All of the ultrasonic instruments used at poolside have a basic time-amplitude scan (A-scan) CRT presentation that indicates the defect depth and response amplitude.

The rate generator (sychronizer) shown in Figure 10.10 is used to simultaneously trigger the pulser and start the horizontal sweep of the CRT. The pulser sends a high voltage pulse to the piezoelectric transducer, which, by the forward piezoelectric effect, generates ultrasonic waves into the specimen

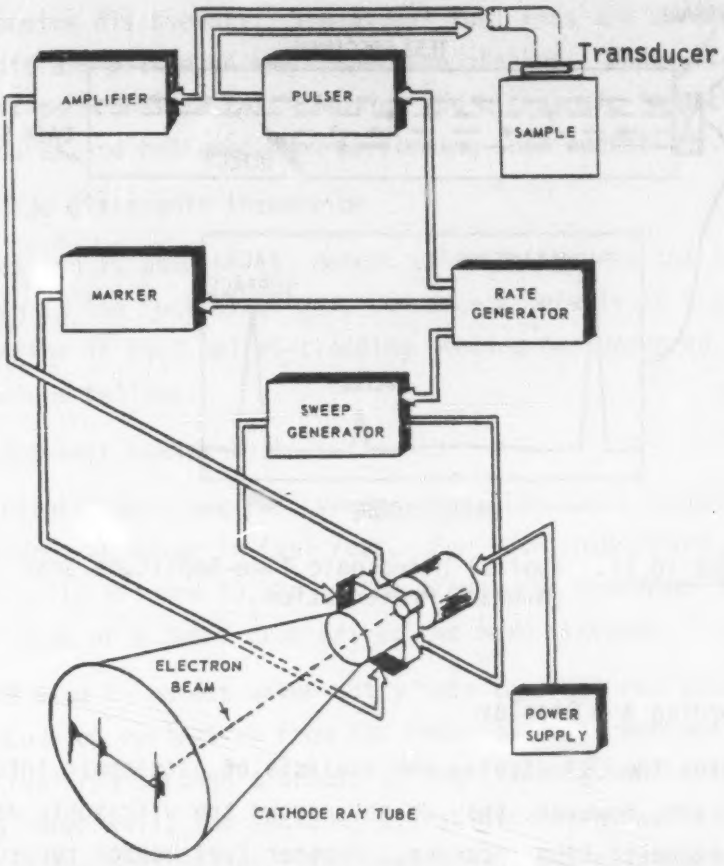


FIGURE 10.10. Functional Diagram of Pulse-Echo Ultrasonic Instrumentation (Ref. 129)

under test. Any returning pulses (echoes) are detected by the reverse piezoelectric effect. This returning signal is amplified and applied to the vertical defection plates of the CRT. The amplitude of the signal displayed on the CRT is proportional to the amount of returning energy incident on the transducer. The position of the received echo on the horizontal display of the CRT indicates the distance traveled by the ultrasound in the specimen.

A typical A-scan presentation is depicted in Figure 10.11. Shown in the figure are the reflection from the front surface, back surface, and the defect. The A-scan presentation shows that the defect is located in the bottom half of the test specimen, based on the position of the front and back surface reflections.

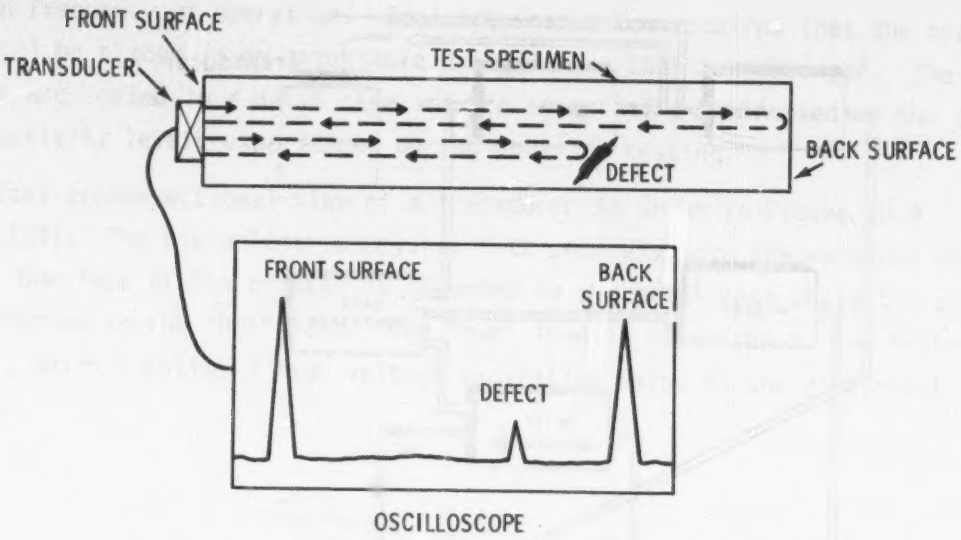


FIGURE 10.11. Typical Ultrasonic Time-Amplitude Scan (A-scan) Presentation

10.2.3 Data Recording and Display

One fuel vendor uses the CRT display for analysis of ultrasonic information during the inspection; however, they do not record the ultrasonic data on a strip chart or a magnetic tape recorder. Another fuel vendor records poolside ultrasonic data using a strip chart and magnetic cassette recorder.

10.3 Ultrasonic Inspection at the Spent Fuel Storage Pool

10.3.1 Remote Inspection Operations

Because of the high radioactivity of irradiated fuel, ultrasonic inspection at poolside requires remote handling equipment, including a fixture (test station) that is positioned in the storage pool. The fixture holds individual fuel rods in a vertical position while the ultrasonic transducers traverse and inspect the fuel rod cladding. The ultrasonic system instrumentation is located adjacent to the spent fuel pool where the test personnel can visually observe the handling, positioning, and inspection operations. A crane is used to transport fuel bundles in the storage pool. Fuel bundles scheduled for ultrasonic

inspection require disassembly. Individual fuel rods are carefully withdrawn from the bundle and placed in the inspection station. Underwater cameras are used to assist personnel in fuel handling and ultrasonic inspection operations. Strict procedures are followed when performing such operations.

10.3.2 Poolside Ultrasonic Inspection

Ultrasonic testing is used to (a) detect water entry into the fuel rod (indicates a breach in the fuel cladding), (b) detect defects in the fuel cladding, and (c) determine if fuel pellet-cladding bonding has occurred. A discussion of each technique follows.

10.3.2.1 Ultrasonic Leaker Test

At domestic plants, only one fuel vendor uses ultrasonic inspection to determine the presence of water in fuel rods. For such inspections, the fuel rod is held vertically (Figure 10.12a). The transducer traverses the length of the fuel rod by means of a motor that drives the head fixture.

The principle used to detect water entry into the fuel rod involves a change in the amplitude of reflection from the inner cladding surface. If water has entered the fuel rod through a breach in the cladding and is in contact with the cladding inner wall, the incident ultrasonic energy would be coupled and transmitted to the fuel pellet. The presence of water in the rod causes a change in the ultrasonic signal at this interface (acoustic signature). Figure 10.12b, shows the oscilloscope presentations of the reflected amplitude

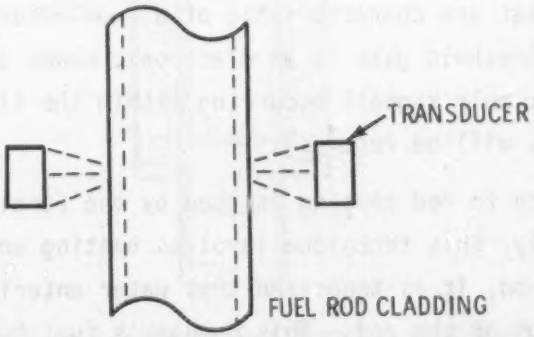


FIGURE 10.12a. Ultrasonic Leaker Test at Poolside

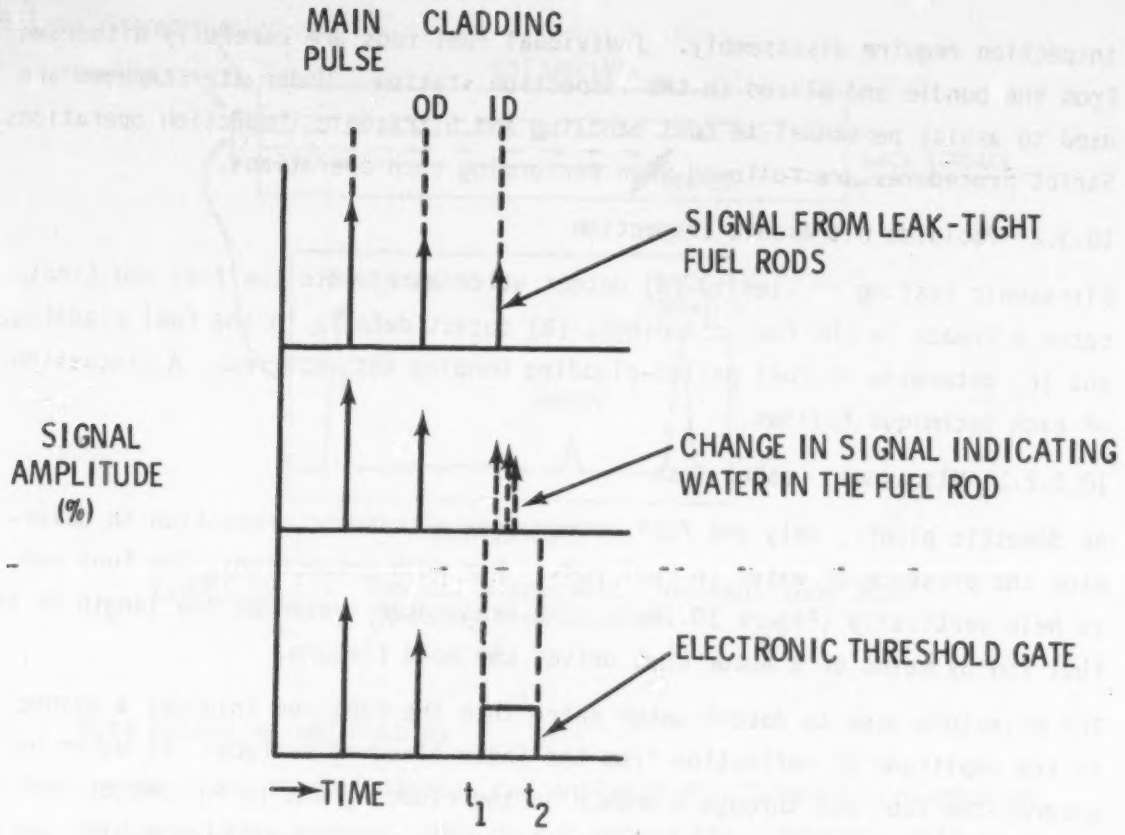


FIGURE 10.12b. Time-Amplitude Scan (A-Scan) Display for Ultrasonic Leaker Test

from the outer cladding wall surface interface and the inner cladding wall surface interface that are characteristic of a "nonleaker" fuel rod and a "leaker" fuel rod. The threshold gate is an electronic means of providing an acceptance "window", whereby only signals occurring within the time gate (i.e., t_1 to t_2 in Figure 10.12b) will be recorded.

A similar approach to rod testing is used by one foreign company at European reactors. Briefly, this technique involves heating and cooling of the bottom end of the fuel rod; it is theorized that water entering the rod would accumulate at the bottom of the rod. This company's fuel bundle is designed so the lower tie plate can be readily removed. Prior to removal of the lower tie

plate, the fuel bundle is turned upside down. The tie plate is removed and a special device for detecting defective fuel rods is placed over each rod to be inspected as shown in Figure 10.13 (Ref. 99). The device is designed so that the ultrasonic beam can be focused to a point on the inner wall of the lower end cap (plug). The principle of operation requires that the heating coils encircling the fuel rod convert any water within the rod to steam. The steam rises until it condenses on the bottom surface of the end cap. Cooling water circulates in the upper portion of the device causing the steam to condense on the inner surface of the end cap. A characteristic acoustic signature response indicates water within the fuel rod. This device has been used to inspect irradiated European LWR fuel for over three years, and was reported to be a successful measurement technique.

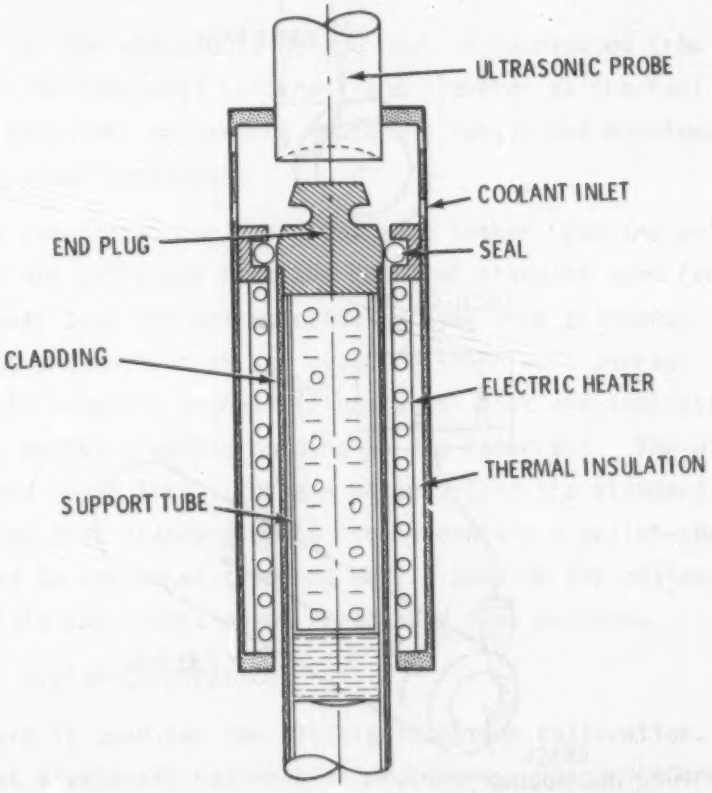


FIGURE 10.13. Special Device Used by a Foreign Company to Find Defective Fuel Rods by Detecting Water Inside the Rods (Ref. 99)

10.3.2.2 Ultrasonic Defect Test

One domestic fuel vendor has performed a limited number of ultrasonic inspections where the ultrasonic transducer was positioned so that shear waves are transmitted circumferentially around the cladding wall. The test was intended to detect axially-oriented defects in the cladding as shown in Figure 10.14. The fuel rod is rotated and translated past the inspection transducer. Defects in the cladding produce signals that can be viewed on the instrument

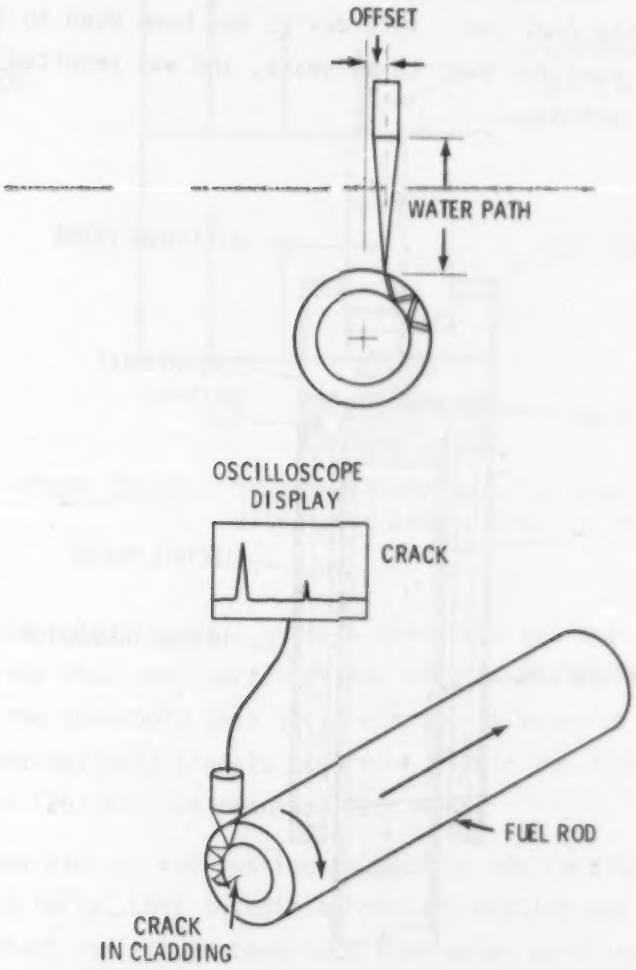


FIGURE 10.14. Ultrasonic Defect Test That Employs 45° Shear Waves

A-scan display (Figure 10.11). The severity (depth) of a given defect indication (signal amplitude) is determined by comparing the signal amplitude of the defect to the amplitude response from artificial, electric discharge machined (EDM) slots in the standard.

10.3.2.3 Ultrasonic Test for Fuel Pellet-Cladding Bonding

One domestic fuel vendor has completed a limited number of pellet-cladding bond inspections (Figure 10.15) at poolside. The principle of operation of this test is similar to that of the ultrasonic leaker test: tight bonding of the fuel pellet to the cladding inner wall enables coupling of ultrasound into the fuel pellet. This causes a loss in signal amplitude at the pellet-cladding interface (Figure 10.15).

10.3.3 Ultrasonic Test Standards

The test standard for the ultrasonic defect test is fabricated from Zircaloy fuel cladding with the same wall thickness and diameter as the fuel rods to be inspected. Axial EDM slots of varying depth and length are machined on the cladding inner and outer surfaces.

The test standards fabricated for the ultrasonic leaker test and pellet-cladding bond test are different from the EDM slot standard used for the defect test. For the leaker test and pellet-cladding bond test standards, an attempt is made to simulate a condition at the cladding inner wall surface that would cause characteristic acoustic signals (signatures) that are indicative of coolant water entry or pellet-cladding bonding at the interface. The ultrasonic leaker test standard would likely contain water within the standard. The pellet-cladding bond test standard would likely contain a pellet-shaped material that is bonded to the inner cladding wall. Some of the pellets may be fractured to simulate the condition of irradiated fuel pellets.

10.3.4 Ultrasonic System Calibration

A detailed procedure is used for the ultrasonic system calibration. Each ultrasonic test has a separate calibration procedure. The procedure includes a step-by-step instruction program for adjusting and establishing proper inspection system sensitivity using the appropriate test standard. System

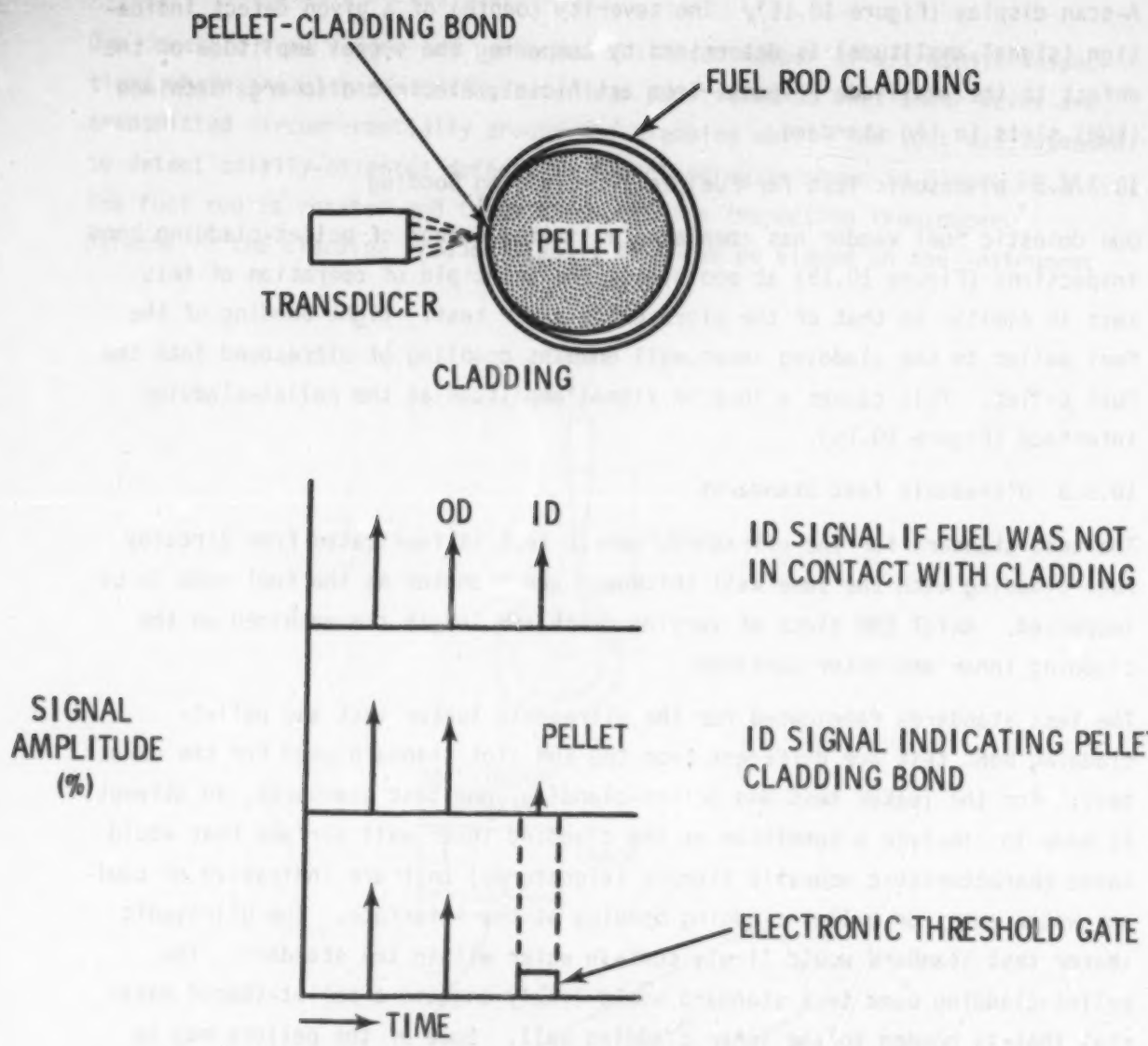


FIGURE 10.15. Ultrasonic Pellet-Cladding Bond Test

adjustments include: (1) ultrasonic instrument, (2) transducer(s), (3) recording and display equipment, and (4) mechanical fixtures and fuel rod transport or positioning device.

During ultrasonic inspection at poolside, the inspection system is periodically checked for calibration sensitivity. Typically, the system would require a calibration check (a) at least once every four hours, (b) whenever a component of the system (e.g., transducer) is replaced, (c) whenever there is a personnel shift change, (d) after a specific number of rods have been inspected, and (e) whenever the operator suspects that the system is not in proper operation.

10.3.5 Fuel Rod Acceptance and Rejection Criteria

10.3.5.1 Defect Test

One domestic fuel vendor indicated that they did not have extensive experience using this technique at poolside. They were generally uncertain about the interpretation of the defect test results because they did not presently have a test standard for use at poolside. This fuel vendor stated that with fuel rods exhibiting some degree of ultrasonically detectable anomalies, those indications occurred at the same axial locations as the indications of pellet-cladding bonding.

This fuel vendor further explained that they had not yet inspected a fuel rod where there was a defect indication of such significance that the rod would be suspected of being a potential leaker. Hence, no fuel rods have been rejected to date using this technique, and a criteria for rejection has not been firmly established. A test standard is now being fabricated and a criteria for acceptance/rejection will be established in the future. This fuel vendor could not comment on the sensitivity and reliability of detection at this time.

10.3.5.2 Leaker Test

Another domestic fuel vendor uses ultrasonic testing to detect water in the fuel rod. If water is determined to be present in the fuel rod, the rod is rejected. This vendor also reviews and compares the eddy current data and visual inspection results before rejecting any fuel rods.

10.3.5.3 Pellet-Cladding Bond Test

One domestic fuel vendor indicated that the pellet-cladding bond test technique has been used to a very limited extent during poolside fuel inspection. Currently there are no criteria established for accepting or rejecting fuel rods

based on the results of this test. This vendor is developing data in the near future on the reliability of this technique.

10.3.6 Frequency of Ultrasonic Inspection

Ultrasonic inspection is not routinely used at poolside fuel inspections. Only two of the five domestic fuel vendors use ultrasonic techniques at poolside.

One fuel vendor explained that if only two fuel bundles in the core were designated as leakers as a result of the sipping test, nondestructive examinations (ultrasonic, eddy current, etc.) would not likely be performed on those bundles, and the leaker fuel bundles would simply be replaced with new fuel bundles. This fuel vendor indicated that they are interested in performing ultrasonic or eddy-current testing when they feel that the failure mechanism is perhaps different than that experienced in the past. For example, hydride failures were common with some fuel manufactured prior to 1975. Today fuel rod failures due to pellet-cladding interaction are being studied.

One fuel vendor stated that when fuel rods fail and complete bundles are replaced, there is an obvious economic penalty accrued by the fuel vendor. However, this must all be weighed against the cost-benefit of a nondestructive inspection program. Ultrasonic testing is sometimes used by one fuel vendor to inspect selected rods from lead test fuel bundles (Ref. 102).

One fuel vendor stated that they perform the ultrasonic defect test and pellet-cladding bond test on all of the fuel bundles they disassemble at poolside. That vendor explained that on a per year basis, fuel bundles are disassembled at approximately half of the plants at which they perform fuel inspections.

10.3.7 Time and Personnel Requirements

One fuel vendor's experience indicates that it requires approximately one minute per fuel rod to perform the leaker test after the equipment is set up. This inspection requires a two-person team, one to operate the inspection station while the second watches the instrument oscilloscope display. This vendor stated that often the rod will be re-examined, and the inspectors will try to pinpoint the defective area of the rod. Thus, a one-minute inspection rate is the minimum time required for the examination of a single fuel rod.

Another fuel vendor stated that it requires a few minutes to perform the defect test and pellet-cladding bond test per fuel rod. For these tests, this vendor uses a two-person team.

10.4 Limitations to Ultrasonic Testing

As was the case with eddy-current inspection, each of the poolside ultrasonic inspection techniques requires that the fuel bundle be disassembled so fuel rods can be individually tested.

One fuel vendor presently uses a focused transducer with a 0.38-mm diameter beam at the focal point to perform the defect test. The fuel rod is rotated at 3000 rps (with 4200 rps the maximum permissable). At the current rotation rate of 3000 rps and with a beam overlap of 0.127 mm, a total (100%) volumetric inspection of the fuel rod cladding requires 100 revolutions to traverse 25.4 mm. To traverse the entire active length of the fuel rod (typically 3658 mm) would take 4.8 hours per rod. Inspecting 100 rods would take approximately 3 weeks working 24-hour days. Thus, the 100% volumetric defect test is presently impractical.

That vendor stated that they were uncertain as to the reliability of the pellet-cladding bond test. Their experience shows that a pellet-cladding bond test indication can be caused by any of the following conditions: a rough cladding outer surface inhibiting the incident ultrasound, a rough cladding inner surface dispersing the ultrasonic signal, or a nonreflective inner surface due to an acoustical bonding of the pellet surface to the cladding inner surface.

The fuel vendor further stated that evaluating the characteristics of the ultrasonic back-reflection patterns on an oscilloscope made it possible to eliminate a rough cladding outer surface as a significant contributor to the bonding indications. The bonding indications were therefore thought to be caused by a condition existing on the inner surface of the cladding, either a corrosive type surface roughening or sufficient bonding to transmit acoustic waves.

The vendor also indicated that when performing the ultrasonic defect test it is important that the alignment of the system is correct. Standards are needed to assure precision alignment and were not available when the initial tests were done. This vendor will require that system alignment be checked periodically after a certain number of rods have been inspected. Thus additional time will be required to perform these checks.

That fuel vendor also stated that they were concerned with the condition of the cladding outer and inner wall surfaces when performing the defect test. Outer wall surface roughness caused by scratching, fretting at the spacer grid contact areas on the fuel rods, oxide buildup, ridging, etc., would likely cause problems in interpretation of data. These surface anomalies disrupt the ultrasonic beam. Inner wall surface roughness such as scaling or fabrication process marks cause reflections that can complicate the interpretation of test results.

Another fuel vendor stated that in performing the ultrasonic leaker test it is the responsibility of the data analyst to interpret the A-scan data during fuel rod inspection. There is no analog strip chart recording of data. [PNL comment: There is the possibility that the person interpreting the data could miss an indication if that person were distracted for some reason.]

10.5 Poolside Inspection Hazards

Ultrasonic inspection does not alter its subject. There are no apparent hazards in performing ultrasonic inspection. The greatest potential hazard to fuel integrity is not the inspection itself but the associated remote handling and transport operations with fuel bundles and rods.

10.6 Hot Cell Ultrasonic Inspection

10.6.1 Use of Hot Cell Inspection

Hot cell and poolside ultrasonic inspection results are compared to the metallographic results from hot cell destructive examinations. The metallographic results are used to confirm the nondestructive test data and provide the means for determining ultrasonic inspection sensitivity and reliability of detection.

In addition, destructive examination data are used to help establish the criteria for acceptance and rejection of fuel rods and to characterize degradation mechanism.

10.6.2 Ultrasonic Inspection

There was little information in the publicly available literature on ultrasonic inspection of irradiated fuel in the hot cell. One paper reported on ultrasonic testing used in a hot cell for irradiated fuel inspection (Ref. 130). In that study, the ultrasonic defect test was employed to determine if small incipient type defects could be detected by employing a pulse-echo technique using 15 MHz to generate 45^{0} shear waves as shown in Figure 10.16. Metallographic sectioning was performed on selected fuel rods with strong ultrasonic indications.

10.6.3 Ultrasonic Detection Sensitivity

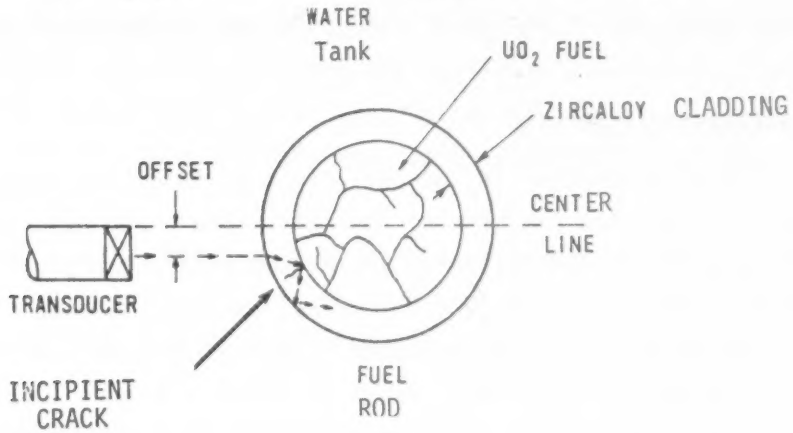
The initial tests described in Reference 130 were performed with selected specimens to show the feasibility of using ultrasonic testing to detect cracks in fuel rod cladding. One specimen with cracked UO_2 pellets had an axial EDM slot (0.40-mm long and 0.04-mm deep) machined on the inner cladding surface.

Figure 10.17 shows the pulse-echo, A-scan display signals from a specimen with a circumferential ridge on the outer cladding surface, a signal from the EDM slot on the inner cladding surface, and a signal from the cracked UO_2 pellet fuel in the specimen (Ref. 130).

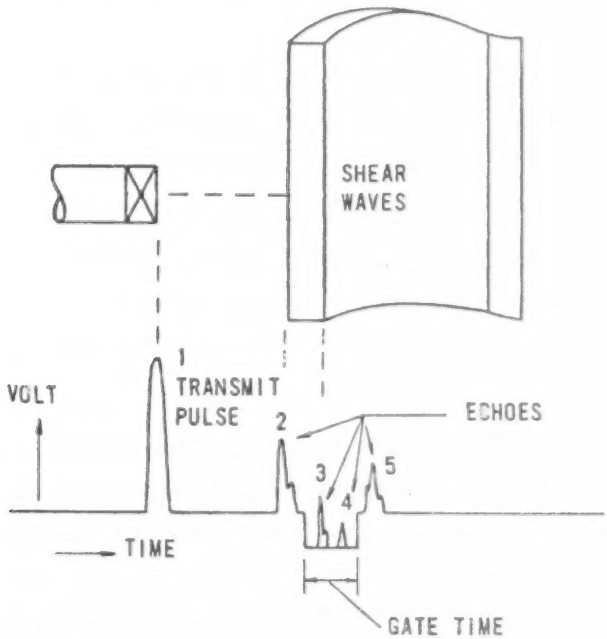
Based on the results of the feasibility study, the ultrasonic system was calibrated using a test standard with an axial EDM slot (0.40-mm long by 0.05-mm wide, by 0.04-mm deep) machined on the inner cladding surface of an unirradiated fuel rod with Zircaloy-4 cladding. It was reported that defects could be located with a longitudinal accuracy of ± 1 mm and circumferential accuracy of $\pm 45^{0}$.

10.6.4 Ultrasonic Inspection of Irradiated Fuel

In the study described in Reference 130, two series of ultrasonic inspections on irradiated fuel rods (burnup was 788GJ/kg of heavy metal (U)) were conducted. The results from one series showed that ultrasonics detected several



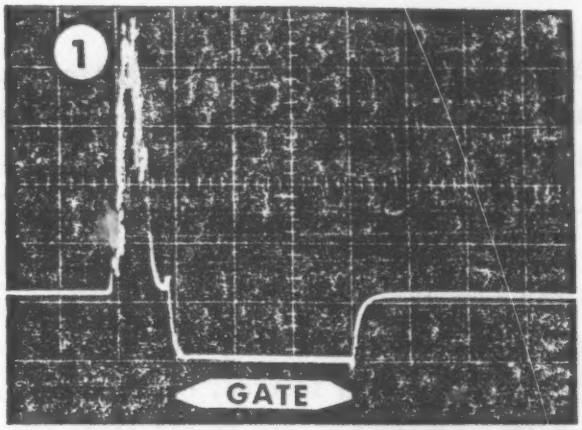
(a) Defect Test Using 45° Shear Waves at 15 MHz



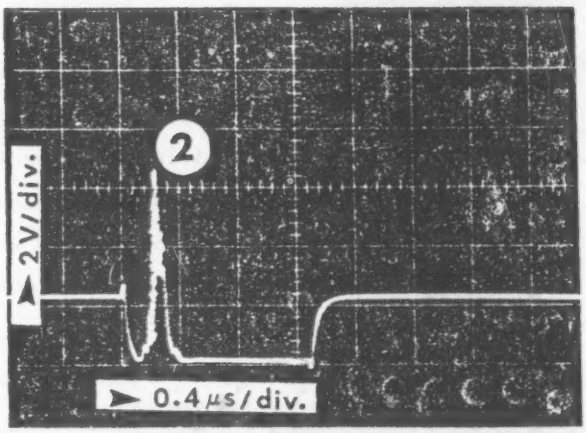
(b) Time-Amplitude Scan (A-Scan)

1. Transmit pulse,
2. Outer cladding surface echo including the circumferential ridge,
3. Echo from inner surface cladding crack,
4. Echo from fuel chip inclusion
5. Echo from a cracked pellet portion contacting the cladding.

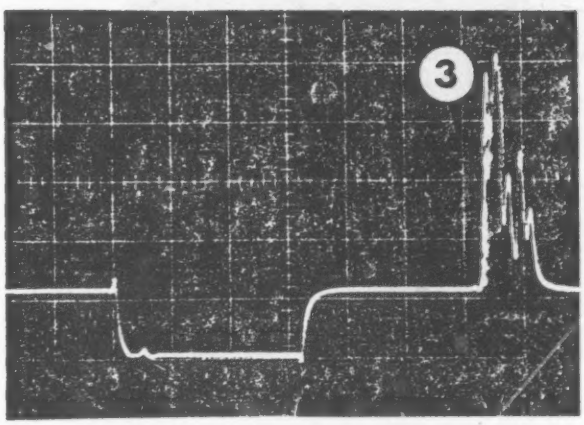
FIGURE 10.16. Ultrasonic Pulse-Echo Defect Test for Fuel Rods (Ref. 130)



Circumferential ridge and cladding outer surface signal inclusive



EDM slot signal on inner cladding surface



signal from material within simulated rod

FIGURE 10.17. Time-Amplitude Scan (A-Scan) Display of Ultrasonic Signals from Rod Specimen Showing (1) Circumferential Ridge and Cladding Outer Surface Signal, (2) Electric Discharge Machined (EDM) Slot Signal on Inner Cladding Surface, and (3) Signal from Material Within Fuel Rod (Cracked UO_2 Pellets With an Aluminum Bar at the Core of the Rod) (Ref. 130)

fuel chips, approximately 20 μm by 150 μm, bonded to the cladding inner wall with an adjacent cladding crack approximately 20 μm deep emanating from the bonded area, as shown in Figure 10.18.

In the second series of tests, irradiated fuel rod cladding (the UO_2 pellets had been removed) produced signals in four specimens that were approximately equal to or greater than the response from the standard EDM slot. The metallographic results from suspect sections confirmed the presence of defects in four of the five specimens. In addition, cladding sections having no apparent defect indications were metallographically examined, and in all cases the metallographic results confirmed that no defects or anomalies existed.

Figure 10.19a (Ref. 130) shows the strip chart recording of the circumferential ridge and incipient cracks. Figure 10.19b shows the A-scan display of the defect signals, while Figure 10.20 (Ref. 130) shows the metallographic correlations of incipient cracks on the inner cladding surface. It was indicated in the report (Ref. 130) that some of the cracks were less than 25 μm deep while others had penetrated to a depth of 60 μm (wall thickness 380 μm). In characterizing these defects as incipient cracks the report stated:

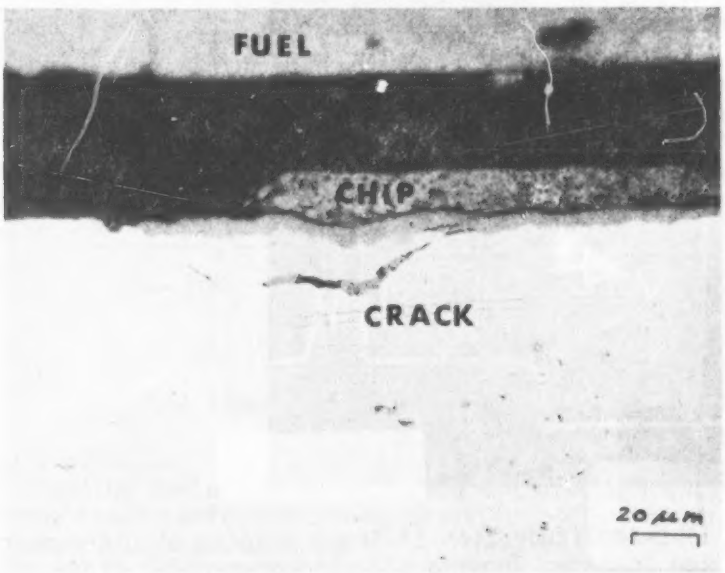
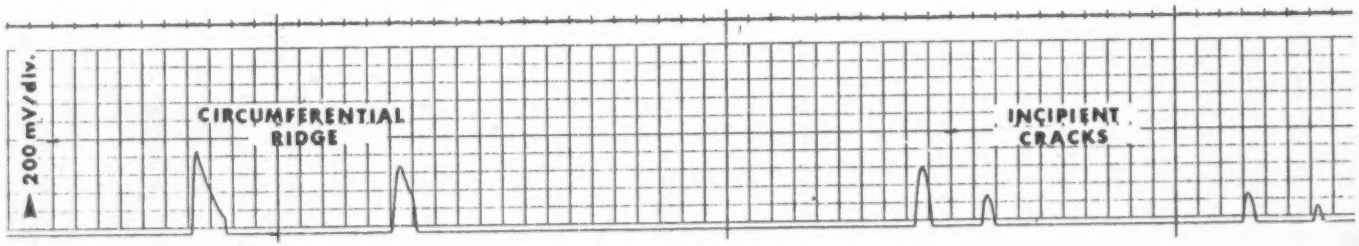
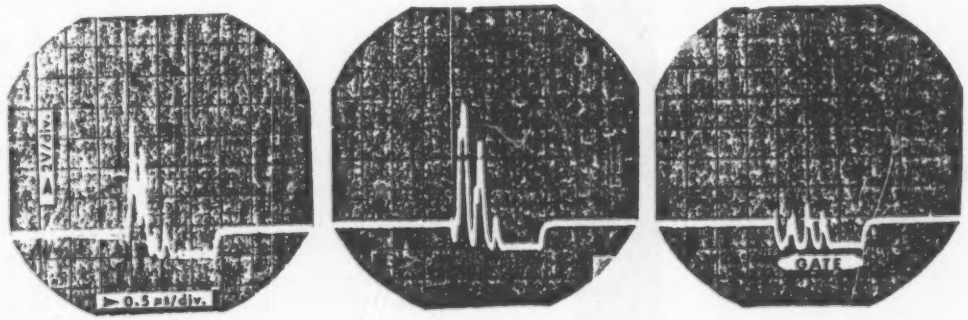


FIGURE 10.18. Fuel Chip and Cladding Crack Detected Ultrasonically in an an Irradiated Fuel Rod Containing UO_2 Pellets (Ref. 130)



Distance along rod (0.37 mm/div)

(a) Strip Chart Record of Circumferential Ridge and Incipient Cracks



(1) (2) (3)

(b) (1) Circumferential Ridge
(2) Incipient Cracks
(3) Incipient Cracks

FIGURE 10.19. Time-Amplitude (A-Scan) Display of Circumferential Ridge and Incipent Cracks (Ref. 130)

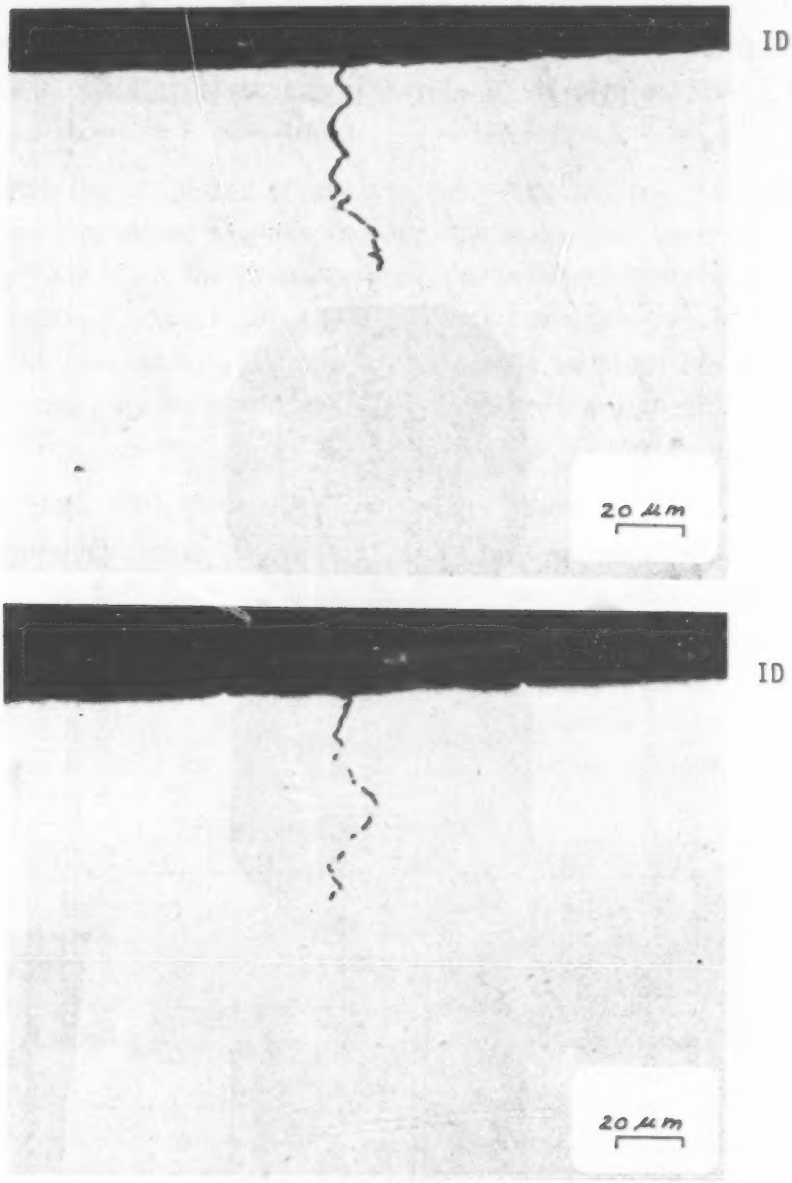


FIGURE 10.20. Metallographic Correlations Showing Incipient Cracks on the Inner Surface of the Cladding (Ref. 130)

"Incipient defects are commonly characterized by absence of hydride/deuteride pick-up from the reactor coolant. Since there was no observable hydride/deuteride concentration associated with these cracks and there was no other evidence of sheath penetration, they were considered to be primary incipient defects. The cracks were located in the vicinity of a circumferential ridge."

The specimen sections had burnups of 439 GJ/kg of U.

Figure 10.21 (Ref. 130) shows the strip chart record and A-scan display of a specimen (burnup 580 GJ/kg of U) with a circumferential ridge. The metallographic results confirmed that the cladding had no defects or anomalies.

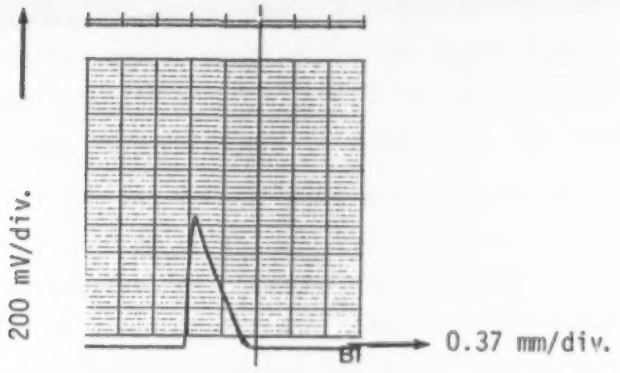
Figure 10.22 (Ref. 130) shows the A-scan display and metallographic results from a bonded fuel chip inclusion (burnup 439 GJ/kg of U). Figures 10.23, 10.24, and 10.25 (Ref. 130) show the A-scan display and metallographic results from a specimen producing large amplitude indications. Metallographic examination of suspect sections confirmed the presence of two hydride/deuteride concentrations and several inner cladding surface cracks. The cracks were reported to be the result of corrosion from coolant water that had entered through the primary defect. This crack had penetrated up to 250 μm in depth (burnup 580 GJ/kg of U).

The results indicated that a routine ultrasonic pulse-echo technique was successfully used to detect defects in irradiated fuel rods when the defects were less than 10% of the wall thickness.

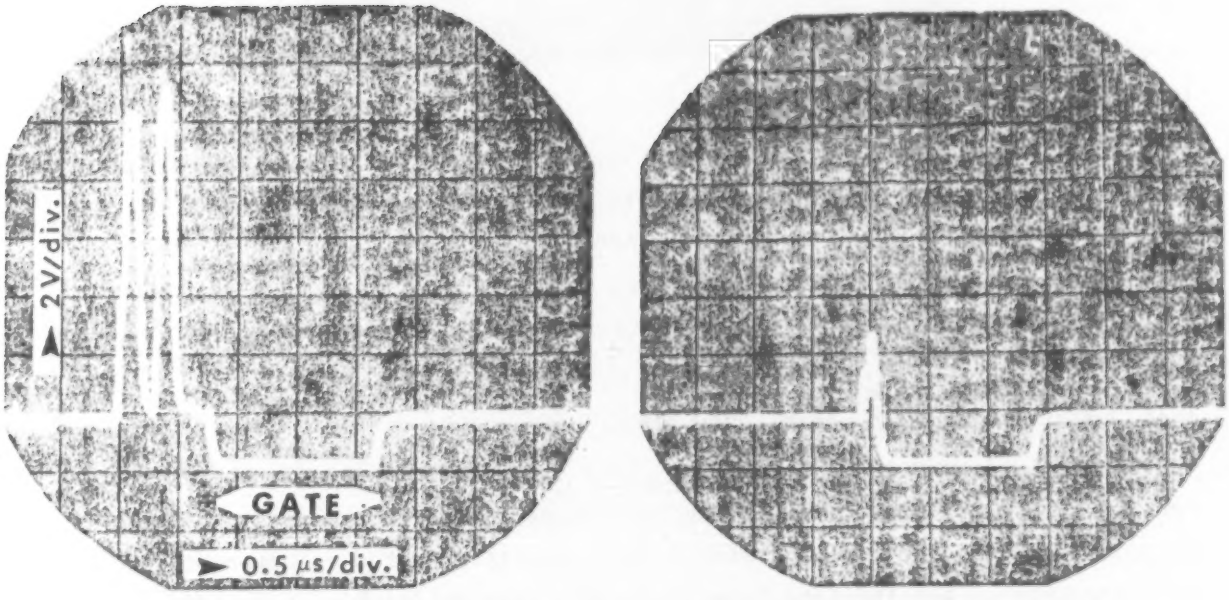
This study showed the potential to ultrasonically discriminate between outer surface circumferential ridge defects, incipient cracks, hydride/deuteride defects, and fuel chips. The metallographic results from this study showed that the ultrasonic inspection technique, using 15 MHz 45^{o} shear waves, was a highly reliable and sensitive method of inspection.

10.7 Future Ultrasonic Capability

Two of the fuel vendors indicated that they did not anticipate further development or use of ultrasonic inspection techniques beyond the current capabilities at poolside. The hot cell ultrasonic test results reported in Reference 130 were encouraging and indicate that ultrasonic testing has demonstrated a capability to play an important role in postirradiation testing and possibly at poolside. It would appear that the ultrasonic leaker test system used by one of those two vendors has thus far proven to be adequate for detecting failed fuel rods. Because of the limited experience at poolside using both the ultrasonic defect test and pellet-cladding bond test, little can be stated about the



(a) Strip Chart Record of Circumferential Ridge



(b) Time-Amplitude Scan (A-Scan) Display of Circumferential Ridge

FIGURE 10.21. Circumferential Ridge Signal Showing the Lack of This Indication to Enter the Time-Gated Region (Metallography confirmed that the cladding was free of defect or anomalies) (Ref. 130)

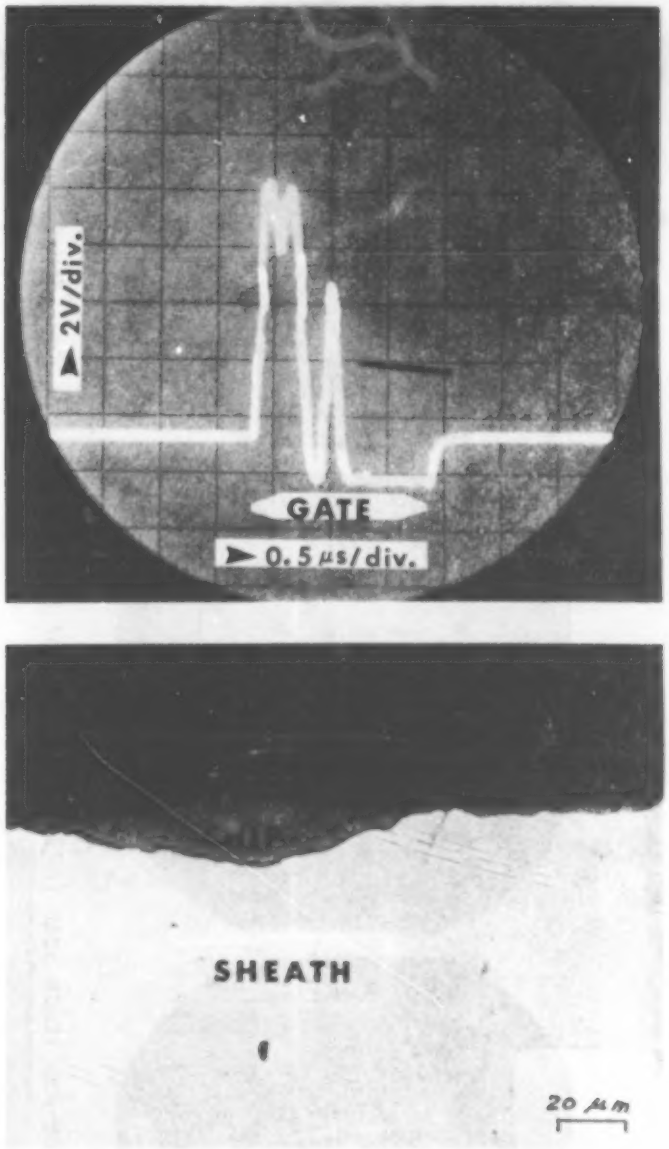


FIGURE 10.22. Fuel Chip Inclusion: (a) Gated Signal; Horiz. 0.5 μs/div., Vert. 2 V/div., and (b) Metallographically Observed Fuel Chip (Ref. 130)

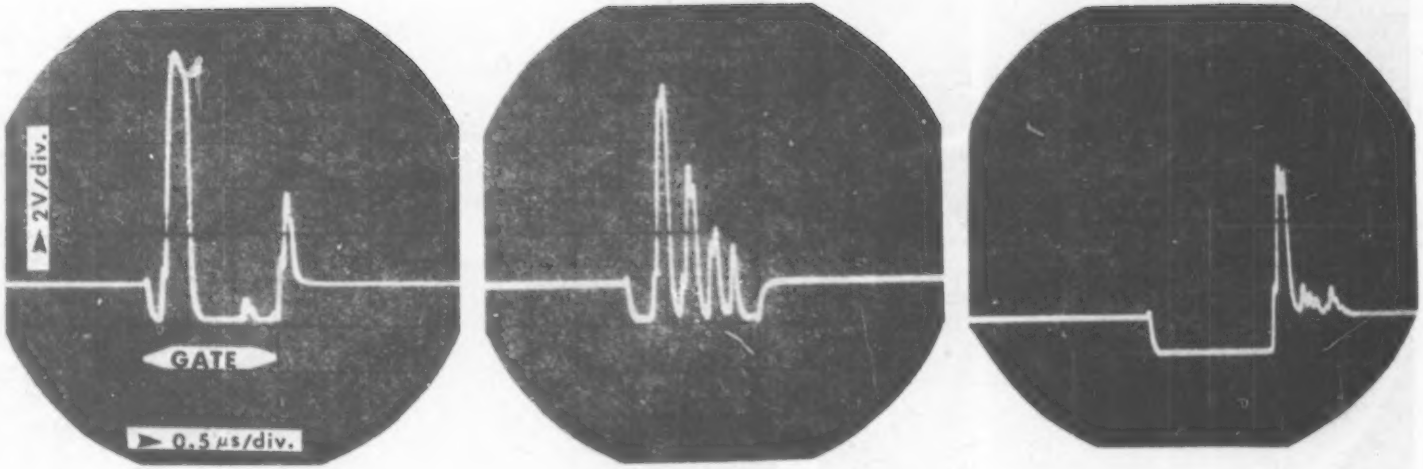


FIGURE 10.23. Time-Amplitude Scan (A-Scan) Display of Hydride/Deutride Concentrations (Ref. 130)

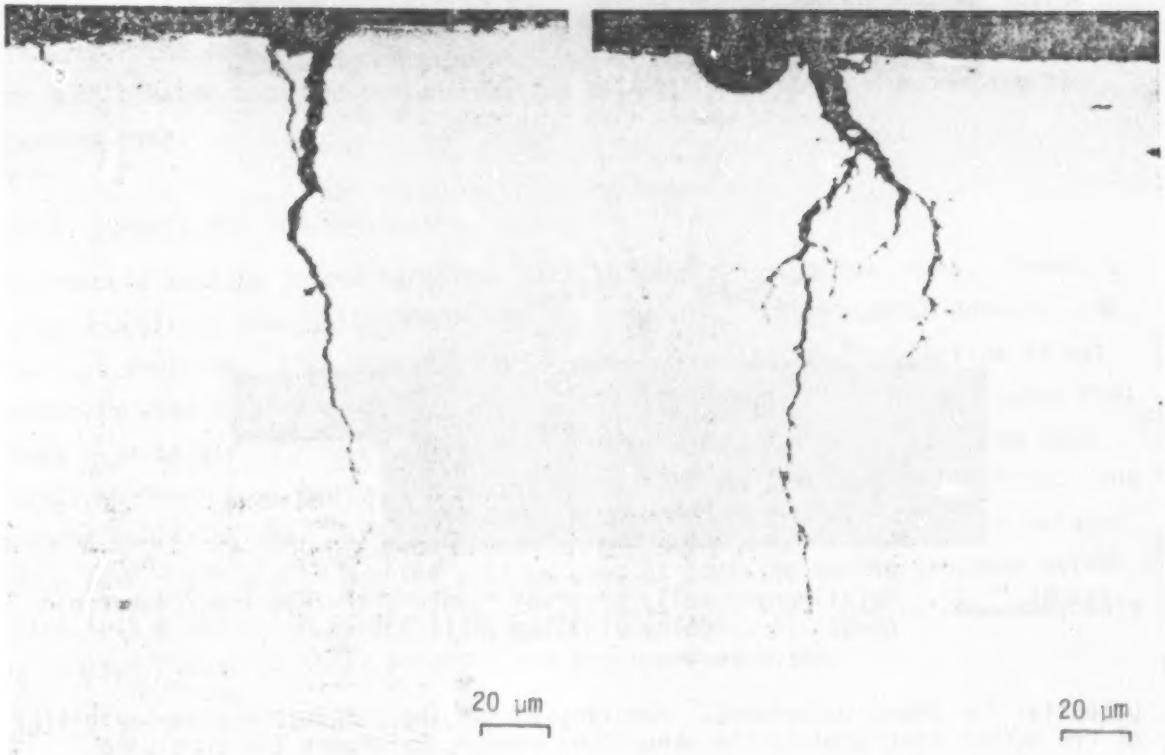


FIGURE 10.24. Cracks in Zircaloy Cladding Associated with "Sunbursts" (Hydrided/Deuterided Areas) (Ref. 130)

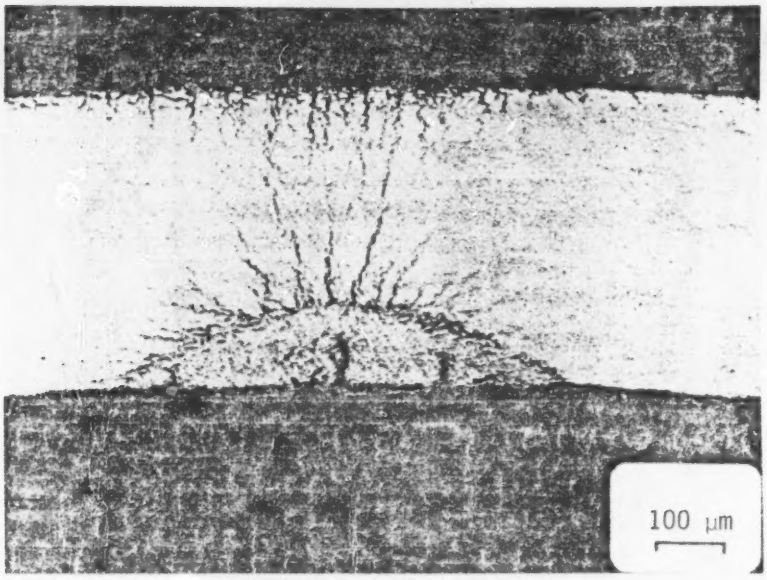


FIGURE 10.25. Metallographically Observed "Sunbursts" (Hydrided/Deuterided Areas) in Zircaloy Cladding (Ref. 130)

potential for these techniques. However, as for the future poolside capability of the defect test used by the other fuel vendor, Reference 130 concluded:

> "Ultrasonic testing has a high potential for further development. A 'museum' of typical defect signals (including a frequency analysis) documented with metallographic features could allow for a reliable interpretation of signals without a destructive examination. This may lead to a complete nondestructive test of irradiated fuel rods which are periodically inspected through several successive irradiations to observe how defects develop. Such a technique will be a powerful tool for assessing potential failure mechanisms."

Recently there have been several published studies (Refs. 131, 132, and 133) that show results obtained using computer analysis techniques for the interpretation and evaluation of ultrasonic signal information. This advanced analysis approach could possibly improve upon current poolside inspection capability.

It was stated in Section 10.4 that one limitation of the ultrasonic defect test is that it would require 4.8 hours to perform a 100% volumetric test using a single transducer. A multiple transducer system could be built to alleviate this problem. An improved system for positioning (alignment is critical),

holding, and rotating the fuel rod could be built so the rod could be tested in either the vertical or horizontal position. Rod rotation rates could likely be much greater than the current maximum of 4200 rps, thereby decreasing the testing time.

10.8 Summary and Conclusions

Ultrasonic testing is one technique used to detect leaker fuel rods. There is little publicly available information on ultrasonic inspection of domestic LWR fuel at poolside. Like eddy-current inspection, ultrasonic inspection is not normally used during poolside fuel inspections. One fuel vendor indicated that they plan to use ultrasonic inspection (defect test and pellet-cladding bond test) whenever fuel bundles are disassembled at poolside fuel inspections. The vendor estimated that this would likely occur at half of the refueling outages each year. Ultrasonic testing will be used at poolside during the more extensive fuel examination programs associated with lead fuel bundles; however, only a limited number of these programs are performed each year.

10.8.1 Ultrasonic Inspection Comparisons

The following conclusions about poolside ultrasonic inspection can be drawn:

- The ultrasonic leaker test is a rapid means of inspecting a fuel rod to assess rod leak-tight integrity.
- Many irradiated rods have been inspected using the ultrasonic leaker test but only a limited number of rods have been inspected using the ultrasonic defect test and pellet-cladding bond test.
- Test standards are currently being developed for the defect test and pellet-cladding bond test. Thus, the reliability and sensitivity of these techniques are undetermined at this time. In addition, criteria for acceptance or rejection of fuel rods based on use of these techniques are not defined.
- Ultrasonic inspection in the hot cell has shown the potential to detect incipient defects that are less than 10% of the wall thickness.

READEX FICHE

10.8.2 Failed Fuel Comments

The ultrasonic leaker test is used by only one of the domestic fuel vendors, and in this case it is used as a supplement to eddy-current testing. This vendor indicated that the technique has proved to be adequate for detecting leaker rods.

11. BWR FUEL CHANNEL INSPECTION

11.1 Introductory Comments

In a BWR, Zircaloy fuel channels define the coolant flow path, provide structural strength to the fuel bundle, and act as a guide for the control blades. Dimensional changes in the channel (such as channel bow) could result in control blade interference, flow blockage, and interference (vibration interaction) with in-core instrumentation leading to possible malfunctioning of the instruments and asymmetric test data. Currently, dimensional and visual techniques are used at poolside to monitor channel performance. During the last four years, new channel dimensional inspection systems have been introduced and tested at commercial BWR's. Borescope, periscope, and television equipment are visual techniques used to monitor channel surface conditions.

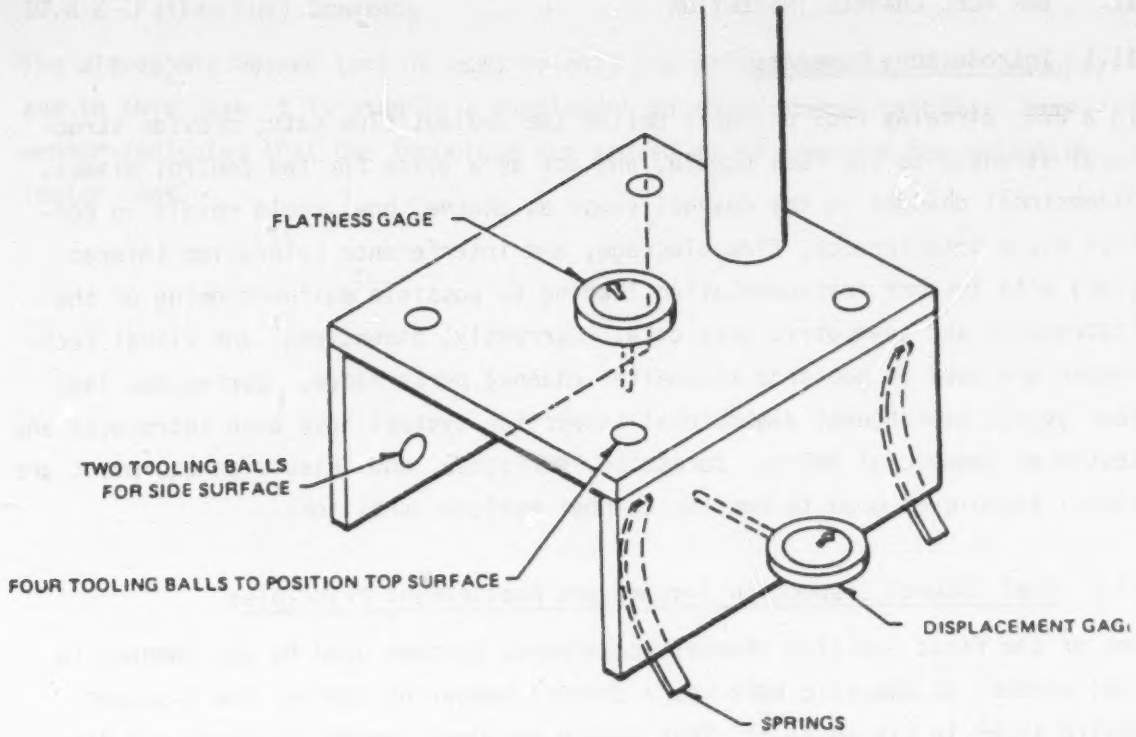
11.2 Fuel Channel Inspection Systems and Measurement Principles

One of the first poolside channel measurement systems used by one company (a fuel vendor) at domestic BWRs was a channel measuring saddle, the U-shaped device shown in Figure 11.1. This device measured channel flatness and displacement.

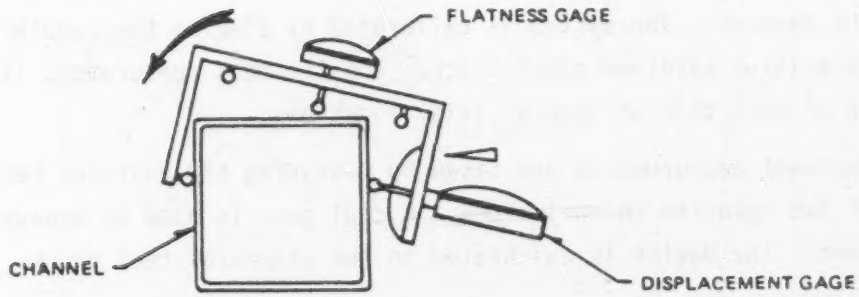
The flatness measurement for each side is obtained from a dial gage mounted on an aluminum plate, which is supported by four tooling balls in contact with one side of the channel. The system is calibrated by placing the saddle onto a standard precision machined steel block. The flatness measurement is taken at the middle of each side at several axial locations.

The displacement measurements are taken by measuring the distance between the centers of two opposite channel sides. A dial gage is used to measure channel displacement. The device is calibrated on the standard steel block.

Recently, that fuel vendor has developed a channel measurement system that uses ultrasonic and eddy-current techniques to measure channel bow, twist, flatness, bulge, length, and oxide thickness. Ultrasonic transducers are used to make channel dimensional measurements; eddy-current probes are used to measure oxide thickness. This new system will replace the older system.



(a) Channel Measuring Saddle



(b) Method for Placing Measuring Saddle on Channel

FIGURE 11.1. Channel Measuring Device Used by One Company (Ref. 102). (Reprinted with permission from the Electric Power Research Institute.)

Two other domestic companies have developed channel measuri g systems that are based on a design developed by a foreign company, which consists of 12 precision displacement transducers (linear variable differential transformer type) mounted on a measuring head, as shown in Figure 11.2 (Ref. 99). The measuring head moves vertically up and down the channel; channel bow, twist, and bulge are determined. The system can also measure axial channel growth (elongation) and oxide thickness. A calibration block is positioned at the bottom of the fixture so the linear variable differential transformers can be calibrated before and after each channel is measured.

11.2.1 Linear Variable Differential Transformer (LVDT)

The LVDT is composed of encircling coils that surround a movable spring-loaded metal core, as shown in Figure 11.3 (Ref. 134). The core is positioned in a

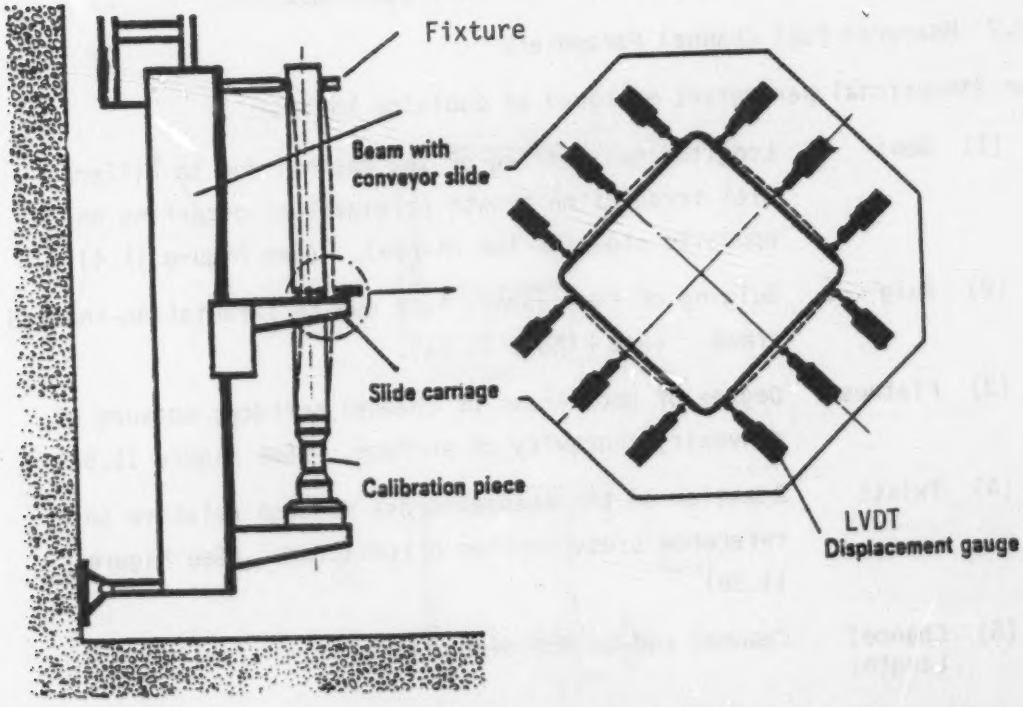


FIGURE 11.2. Schematic View of BWR Channel Measuring Equipment Used by a Foreign Company (Ref. 99)

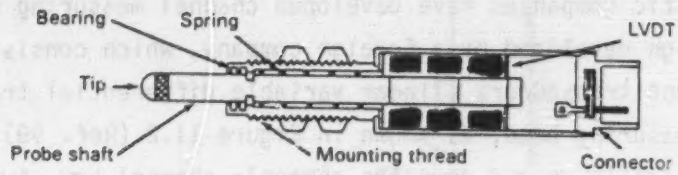


FIGURE 11.3. Cross Section of a Typical Linear Variable Differential Transformer (LVDT) (Ref. 134). (Courtesy of Schaevitz Engineering, Pennsauken, New Jersey.)

shaft with the tip of the core in contact with the channel surface being measured. Any movement of the core as a result of surface variations alters the electromagnetic properties of the LVDT, and this change produces an electrical signal output. The LVDTs used at poolside are commercially available ultra-precision devices designed to withstand the hostile environment (radiation, temperature, vibration, shock) experienced at poolside.

11.2.2 Measured Fuel Channel Parameters

Major dimensional parameters measured at poolside include:

(1) Bow: Longitudinal bending of the channel due to differential irradiation growth (elongation) occurring on opposite sides of the channel. (See Figure 11.4).

(2) Bulging: Bulging of the channel face due to irradiation-induced creep. (See Figure 11.5a).

(3) Flatness: Degree of smoothness of channel surface; measure of convexity/concavity of surface. (See Figure 11.5a).

(4) Twist: Rotation of the channel cross section relative to a reference cross-section orientation. (See Figure 11.5b).

(5) Channel Length: Channel end-to-end distance.

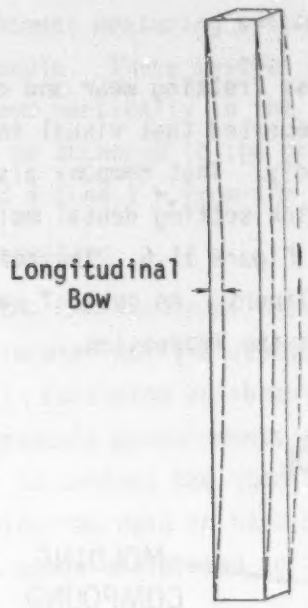


FIGURE 11.4. Longitudinal Fuel Channel Bow

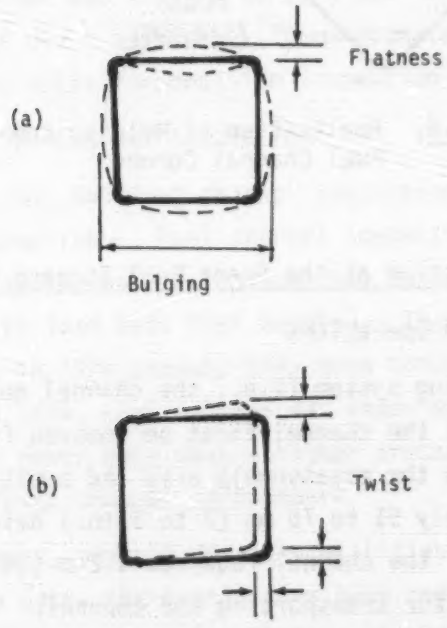


FIGURE 11.5. Fuel Channel Flatness, Bulging, and Twist

11.2.3 Channel Visual Inspection

Visual inspection is used to assess fretting wear and corrosion on channel surfaces and corners. One company reported that visual inspection of channels for corner wear can be performed rapidly. That company also makes impressions of corner wear defects by using a quick setting dental molding compound, applied to the channel corner as shown in Figure 11.6. The defect impression is measured at the site with vernier calipers. An optical comparator is sometimes used in the laboratory to evaluate the impression.

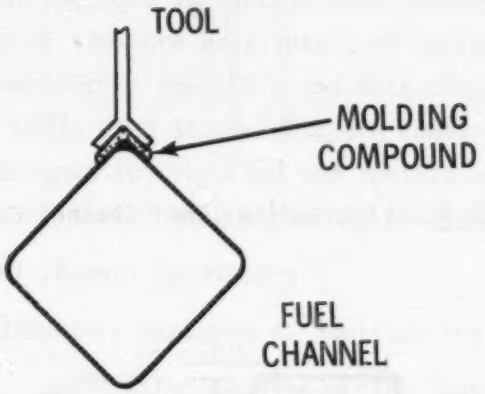


FIGURE 11.6. Application of Molding Compound to Fuel Channel Corner

11.3 Fuel Channel Inspection at the Spent Fuel Storage Pool

11.3.1 Remote Inspection Operations

The older channel measuring system (i.e., the channel measuring saddle) used by one company requires that the channel first be removed from the fuel bundle. The channel is moved from the disassembly area and positioned horizontally in the fuel pool approximately 51 to 76 mm (2 to 3 in.) below the water surface. Horizontal positioning of the channel requires 4.2 m (14 ft) of pool wall length. A crane is used for transporting the channel.

The new LVDT-equipped channel measuring systems do not require removal of the channel from the fuel bundle. These systems can perform all measurements with the fuel bundle positioned vertically in the channel measurement fixture. The systems are designed to be anchored to the poolside deck and are approximately 10 m long, 1 m wide, and extend 1 m from the pool wall.

11.3.2 Fuel Channel Inspection

The test procedure for the LVDT-equipped channel measuring system requires that the system first be calibrated using a standard block mounted at the base of the measurement fixture. Following calibration, the LVDT array vertically traverses the 4.5-m long channel; measurements are taken at 0.3-m intervals. One company uses a computer to control the scanning, acquire the data, perform all data analysis, and display the data in hard copy form. When the inspection is complete, the system is again calibrated so that necessary corrections can be made to the data.

One company indicated that they have examined perhaps several hundred fuel channels using their channel measuring system. They reported that the maximum bulge measurement observed was 1.65 mm to 1.78 mm. That company stated that they almost exclusively use a borescope (70-mm diameter objective lens) with a resolution of in 0.4 mm units for poolside inspection of channels.

11.3.3 Frequency of Fuel Channel Inspection

One company indicated that BWR fuel channel inspection is not normally performed during fuel inspections. Fuel channel inspection is performed on selected channels during the more extensive fuel surveillance programs, such as those associated with lead test fuel bundles. That company started channel inspection at poolside in 1974 because they were concerned about possible channel bulging. Prior to 1974, that company had experienced virtually no channel problems; however, the newer BWRs have a higher pressure drop across the channel wall that could affect channel performance.

Over the past three years, several domestic utilities have purchased channel measuring systems. To date, these utilities have reportedly inspected over 100 channels. Based on the sales to utilities of channel measuring systems, it would appear that poolside fuel channel inspections will increase in the future.

11.3.4 Time and Personnel Requirements

One company reported that it took two hours to measure flatness and bulging per channel with their channel measuring system and required two technicians.

One new LVDT-equipped channel measuring system that is computer controlled could take only ten minutes per channel to perform a complete inspection including flatness, bulge, bow, twist, and length. In addition, five minutes is required for analysis and printout of the data. The inspection operation requires two technicians. The printout time may be used to unload the inspected fuel bundle and load a new bundle onto the fixture. Four channels per hour could therefore be inspected if the replacement can be completed in that time. During initial testing at a commercial BWR, the unload/reload operation took 20 minutes. This was due to the periodic unavailability of labor and the crane for fuel channel movements. The inspection rate during this surveillance program was 8 to 10 channels per 8-hour shift.

11.4 Limitations to Fuel Channel Inspections

Fuel channel inspection is on the critical path of a refueling outage because it requires the use of the spent fuel pool crane. Poolside space is usually very restricted, especially for channel inspection when using the channel measuring saddle.

Seismic bracing has caused interface problems with channel inspection equipment setups at poolside.

11.5 Poolside Inspection Hazards

The measurement process itself does not alter the fuel channel except possibly by introducing scratches. The hazard to the channel is the potential for damage during remote handling operations.

11.6 Summary

Fuel channel inspection at poolside has increased over the past three years. Several utilities have recently purchased channel measuring systems. Much of

the channel inspection is being done by utilities. There are limited data available on channel measurements obtained with the new LVDT-equipped channel measuring systems. The new channel measuring systems appear to have the potential to inspect three or four channels per hour. The inspection rate depends on availability of the spent fuel pool crane for moving of fuel bundles and channels.

Visual techniques are used to inspect for channel corner wear and corrosion. Molding compounds are applied to defective areas, and the defect impression is measured using vernier calipers at poolside.

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5 R. N. Duncan
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Nuclear Fuel Service Dept.
F-92084 Paris la De'fense

H. Knaab, Kraftwerk Union AG
Hammerbacherstr. 12-14
8520 Erlangen
West Germany

W. Uhde
Technischer Uberwachungs-Verein
Norddeutschland E.V.
Postfach 540220
2000 Hamburg 54
West Germany

H. Bock
Atominstitut der Osterreichischen Universitaten
Schuttelstrasse 115
A-1020 Wien
Austria

Joe Dolnicar
Physics Section, IAEA
Post Office Box 100
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Onsite inspection techniques currently used on fuel systems at domestic commercial light-water reactors were assessed. Those techniques are visual, gamma scanning, sipping, mensural, eddy current, and ultrasonic inspections. The assessment involved a literature survey, meetings with all five reactor fuel suppliers, and visits to three reactor sites.

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